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NASA Conference Publication 2089

Space Missions to Comets

A conference sponsored by
NASA Office of Space Science
and held at the Goddard Space
Flight Center, Greenbelt, Maryland
October 1977

NASA

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BARNARD PICTURES OF HALLEY'S COMET

Taken at Yerkes Observatory
May 4, They Tally with Observa
tion from Times Tower May 5.

VIEWED BY MISS PROCTOR

Negatives Show the Tail Extending
20 Degrees, Equivalent to 24,000,000
Miles in Length.

IN COMET'S TAIL ON WEDNESDAY

European and American Astronomers
Agree the Earth Will Not Suffer in
the Passage.

TELL THE TIMES ABOUT IT

And of Proposed Observations—
Yerkes Observatory to Use Bal-
loons if the Weather's Cloudy.

TAIL 46,000,000 MILES LONG?

Scarfed in a Filmy Bit of It, We'll
Whirl On In Our Dance Through
Space, Unharmed, and, Most
of Us, Unheeding

SIX HOURS TO-NIGHT IN THE COMET'S TAIL

Few New Yorkers Likely to
Know It by Ocular Demonstra-
tion, for It May Be Cloudy.

OUR MILLION-MILE JOURNEY

Takes Us Through 48 Trillion Cubic
Miles of the Tail, Weighing All Told
Half an Ounce!

BALLOON TRIP TO VIEW COMET.

Aeronaut Harmon Invites College
Deans to Join Him in Ascension

MAY SEE COMET TO-DAY.

Harvard Observers Think It May Be
Visible in Afternoon

MAY BE METEORIC SHOWERS.

Prof. Hall Doubts This, Though, but
There's No Danger, Anyway.

YERKES OBSERVATORY READY

Experts and a Battery of Cameras and
Telescopes Already Prepared

CHICAGO IS TERRIFIED.

Women Are Stopping Up Doors and
Windows to Keep Out Cyanogen

(Facsimile headlines from the **New York Times** coverage
of Halley's comet on May 10, 16, and 18, 1910)

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NASA Conference Publication 2089

Space Missions to Comets

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NASA

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1979

Symposium on Space Missions to Comets

FOREWORD

The Symposium on Space Missions to Comets was originally conceived to provide a broad scientific background for a proposed rendezvous mission to Halley's Comet. Such a mission would have provided a unique opportunity to combine a high level of public interest in an astronomical object with close-range study of a comet which typically exhibits the full range of cometary phenomena. Part of the scientific interest stems from the idea that an understanding of the physics and chemistry of comets is very basic to our understanding of the origin of the solar system and perhaps to the origin of life itself. At the present time (1979), it is too late to begin work on a rendezvous mission to Halley's Comet. However, the possibility still exists and plans are going forward for an alternative, important cometary mission - namely, a fly by of Halley's Comet with a closest distance of 100,000 km and the subsequent rendezvous of this same vehicle with periodic comet Tempel 2. As it approaches Halley's Comet, the rendezvous spacecraft will release a probe which will explore the atmosphere and near-nuclear region of Halley's Comet. The rendezvous phase with Tempel 2 could last about a year and end with an experimental landing on the comet's surface.

It is therefore timely that this collection of papers given at the October, 1977, Symposium on Space Missions to Comets held at the Goddard Space Flight Center be made available. These papers represent history, folklore, firm scientific results, speculation, and future plans. While it does not present a complete justification for a space mission to comets, the editors hope that it will assist in bringing about a better understanding of the broad impact of and wide interest in such a mission.

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ABSTRACT

This volume contains papers presented at a Symposium on Space Missions to Comets held at Goddard Space Flight Center in October, 1977. Different aspects of the scientific return from such a mission is discussed in papers by F. L. Whipple, F. L. Scarf, S. Chang, G. B. Field, A. H. Delsemme, and G. B. Wetherill. B. G. Marsden reviews the history of comet observations in general and Halley observations in particular. The ion propulsion system needed to achieve a rendezvous with a comet is described by K. L. Atkins. A short summary of a panel discussion is also presented.

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SCIENTIFIC NEED FOR A COMETARY MISSION

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Today is a scientific golden anniversary for me. During the last months, I have been concentrating an attack on periodic comet Schwassman-Wachmann 1, which stays outside of Jupiter's orbit all the time. Looking through the literature over the past 50 years since it was discovered, I notice that on October 17, 1927, in Harvard Announcement Card number 33, my first published scientific contribution appeared. So today is the golden anniversary of my first publication. I don't expect that to impress Dr. Öpik very much, however.

I will be rather simple and direct in this presentation. Two of the speakers asked whether I would describe a comet and give some of the basic information about it, so I shall do so. I admit that this account will be biased to some extent, but I will not have time to be at all complete, nor to give the arguments supporting many of the statements. Figure 1 shows the comet that surprised everybody in 1910 by appearing just before the long expected Comet Halley. That comet, 1910 I, was an extremely dusty comet. In the figure, the dust is off to the upper left, and to the right, you see the gas or ion tail.

Figure 2 shows an extemely different type of comet, a sun-grazer, Ikeya-Seki, 1965 VIII. The following picture (Figure 3), photographed by the Japanese, shows it coming almost to the Sun. It came so close that the entire tail was extremely curved by Kepler's laws.

Next (Figure 4) are four views of Comet Mrkos, 1957 V, showing the difference between the so-called ion or plasma tail, the straight one in the upper left, and the dust tail curving off to the right. These three comets illustrate the enormous differences in physical appearance among various comets.

Fig. 1.   Comet 1910 I.

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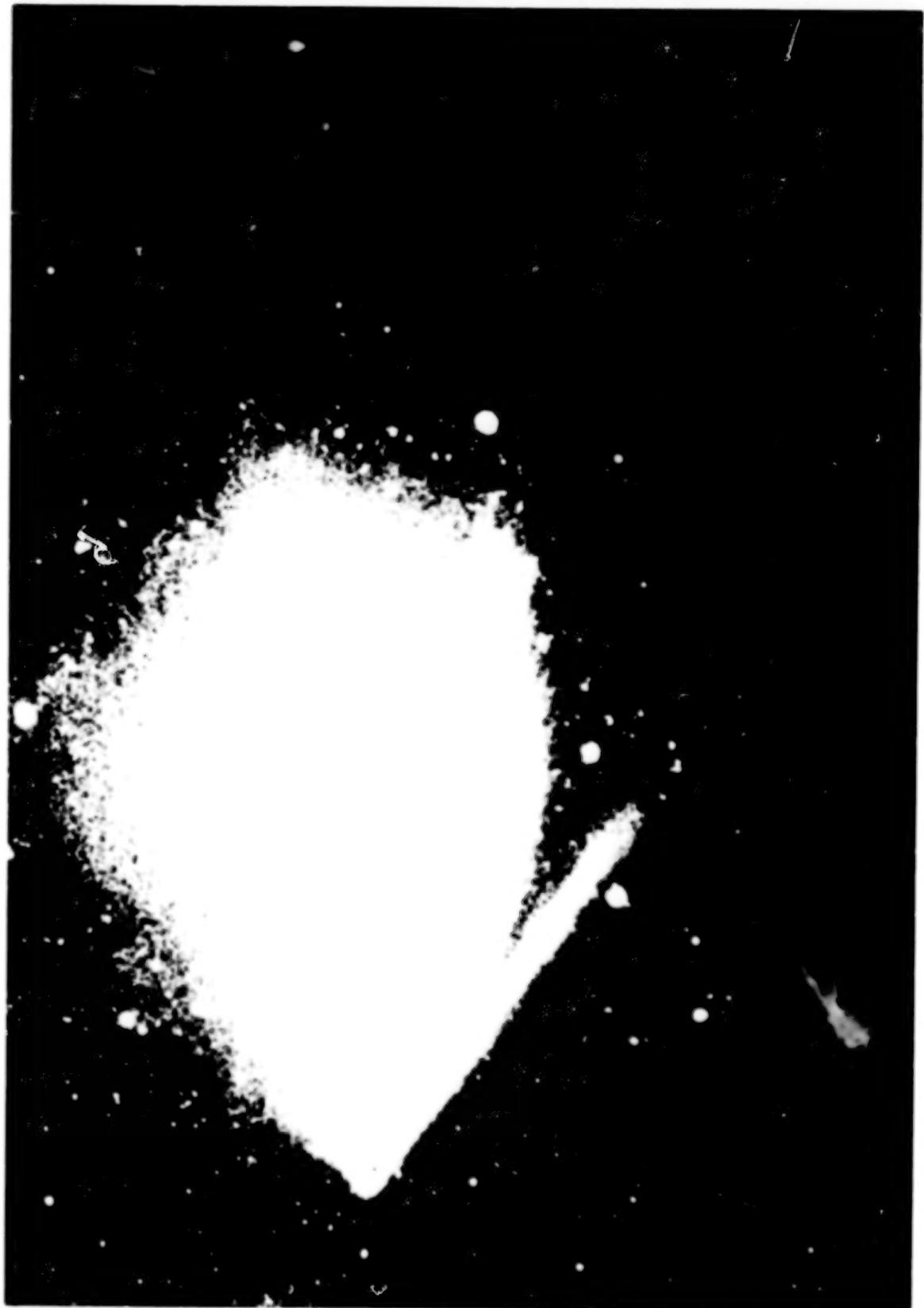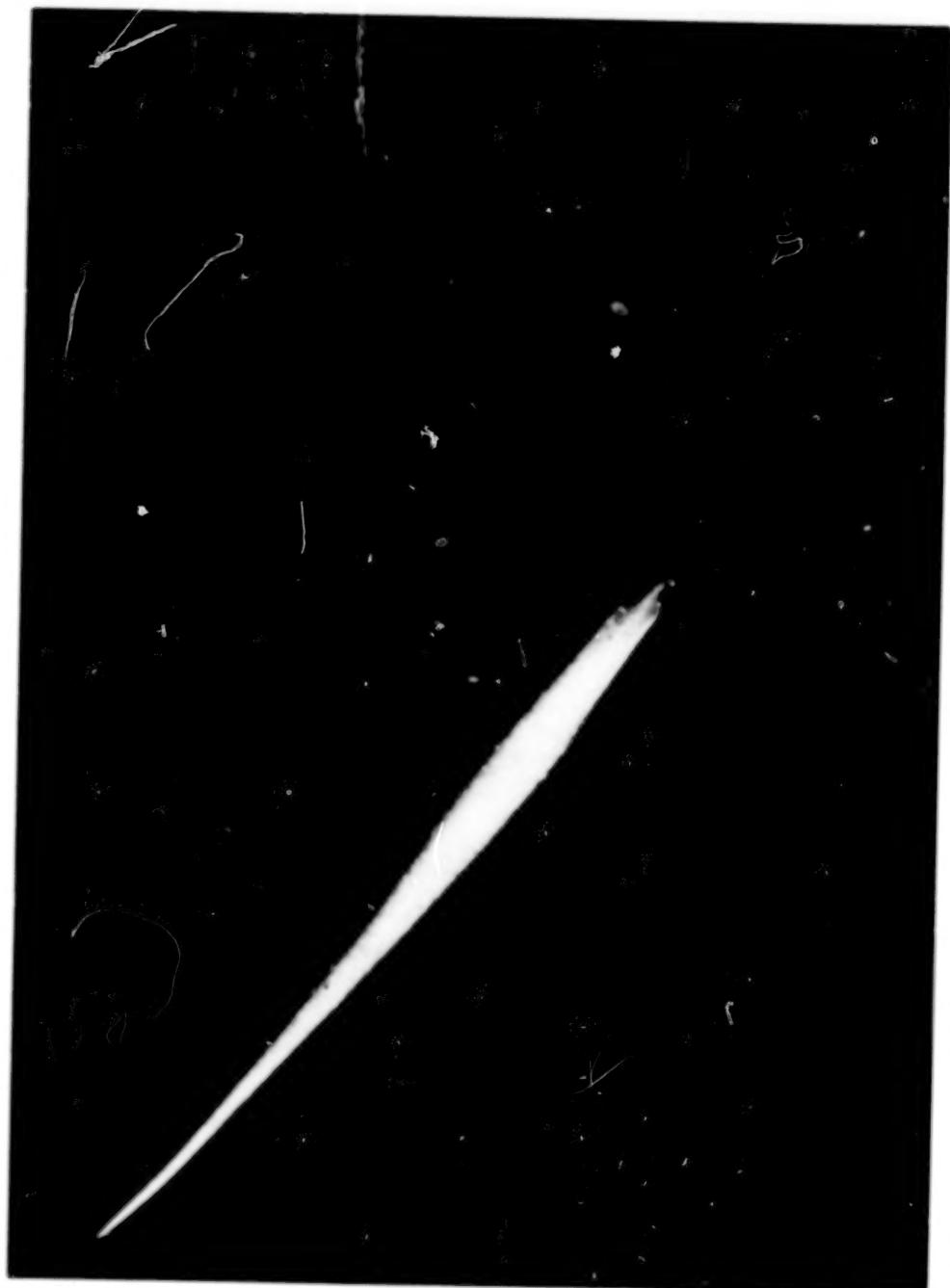
Fig. 2. Comet Ikeya-Seki, 1965 VIII.

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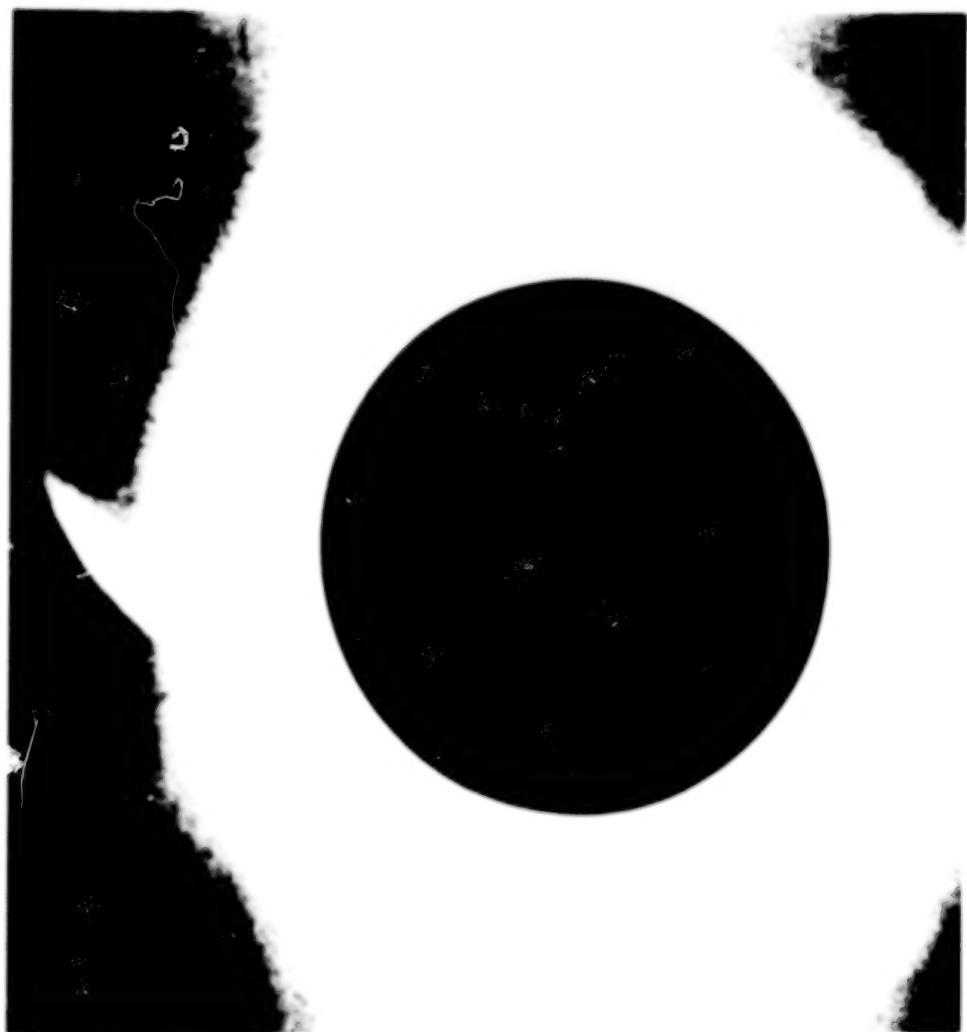
Fig. 3. Comet Ikeya-Seki (1965 VIII) close to the Sun.
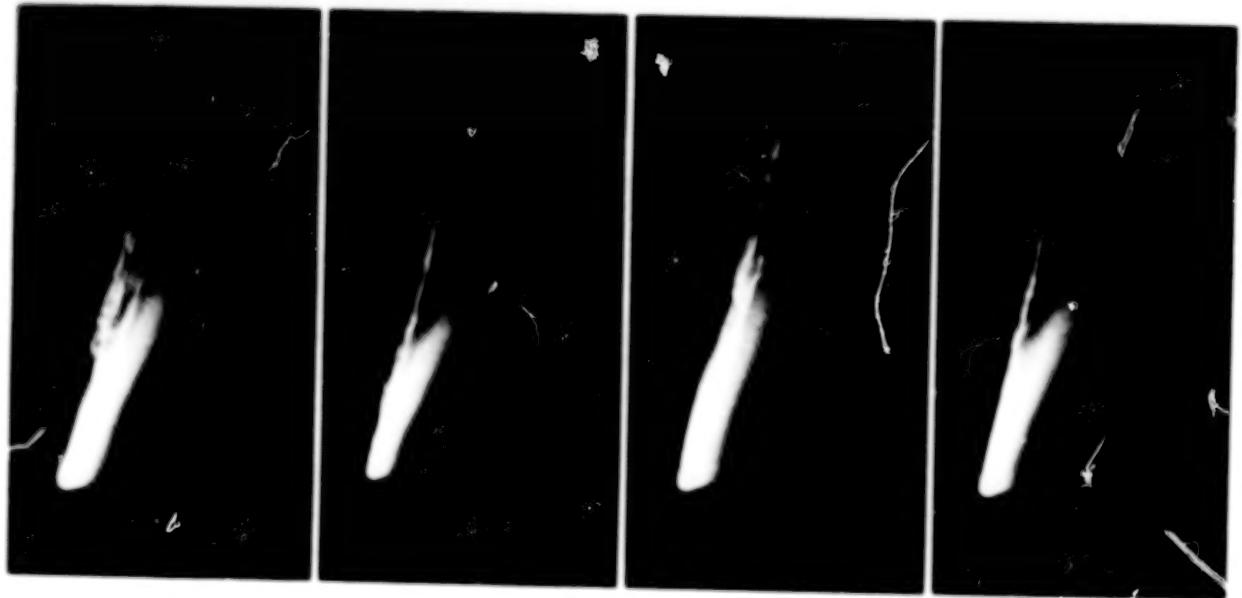
AUGUST 22   AUGUST 24   AUGUST 26   AUGUST 27

Photographed with the 48-inch schmidt telescope

Fig. 4. Comet Mrkos, 1957 V.
(Hale Observatories)

We have in Figure 5 a diagram of a comet. First we note the head or a coma which is the order of 30 thousand kilometers in radius. Gas is sublimated from the invisible nucleus carrying dust with it. The dust is pushed back by solar radiation pressure with a small acceleration so that Kepler's Law causes it to swing far behind, producing the highly curved dust tail.

The plasma tail can extend to as much as 10^8 km or more. I was asked by one of the speakers to define "plasma". As I understand it, a plasma is an ionized gas. In many plasmas, such as the solar wind, the energy involved in the electric and magnetic fields is comparable to the kinetic energy of individual random particle motion. For comets, the energy involved in the magnetic fields and the electric currents can be significant.

For comets, as Biermann showed long ago, the solar wind with its million tons a day of million-degree ionized gas, mostly hydrogen, coming out at some 400 kilometers per second is a plasma that interacts with the outgoing gas from the comet. The comet gas is partially ionized, mostly by the solar wind and somewhat by solar radiation. The first discontinuity in the flow of the solar wind is broad and irregular, the bow wave (Figure 6). Perhaps it is not a real discontinuity. In any case the solar ions first notice the comet near the region of the bow wave. That causes chaotic magnetic fields. Then there is a contact surface near, perhaps very near, the coma in which the ions of the comet strongly interact with solar wind and its magnetic fields. The result is a pressure on the comet ions that carries them away from the Sun with very high accelerations. The accelerations, sometimes more than 100 times solar gravity, remained a puzzle for a

MOTION
OF COMET

COMA
~30000 km

PLASMA TAIL
(UP TO 10^8 km)

SOLAR
RADIATION
AND
WIND

NUCLEUS
~4 km

DUST TAIL
(UP TO 10^7 km)
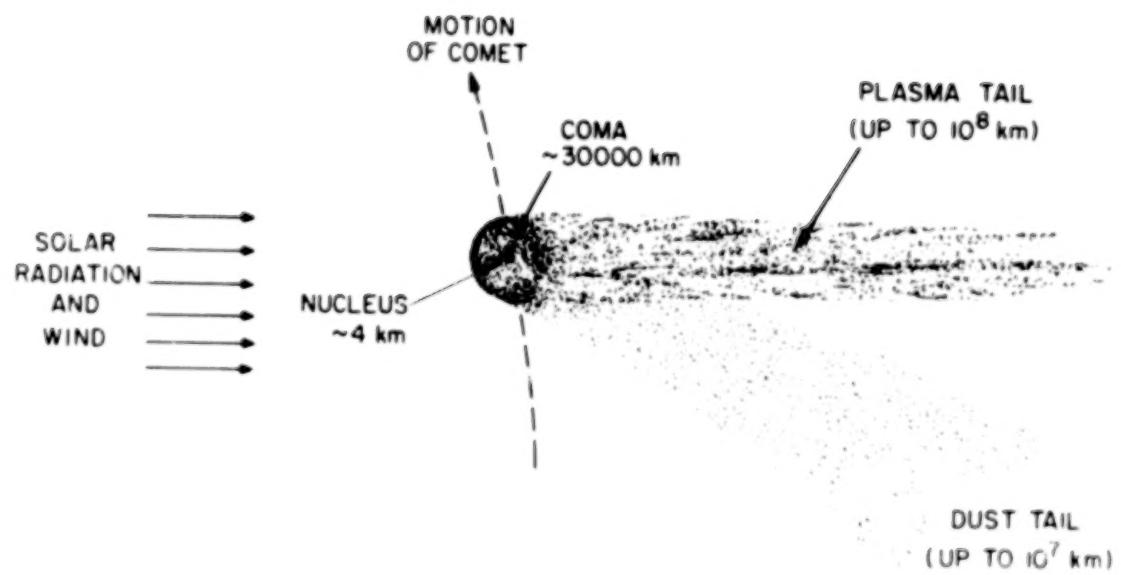
Fig. 5.   Sketch of cometary dimensions.

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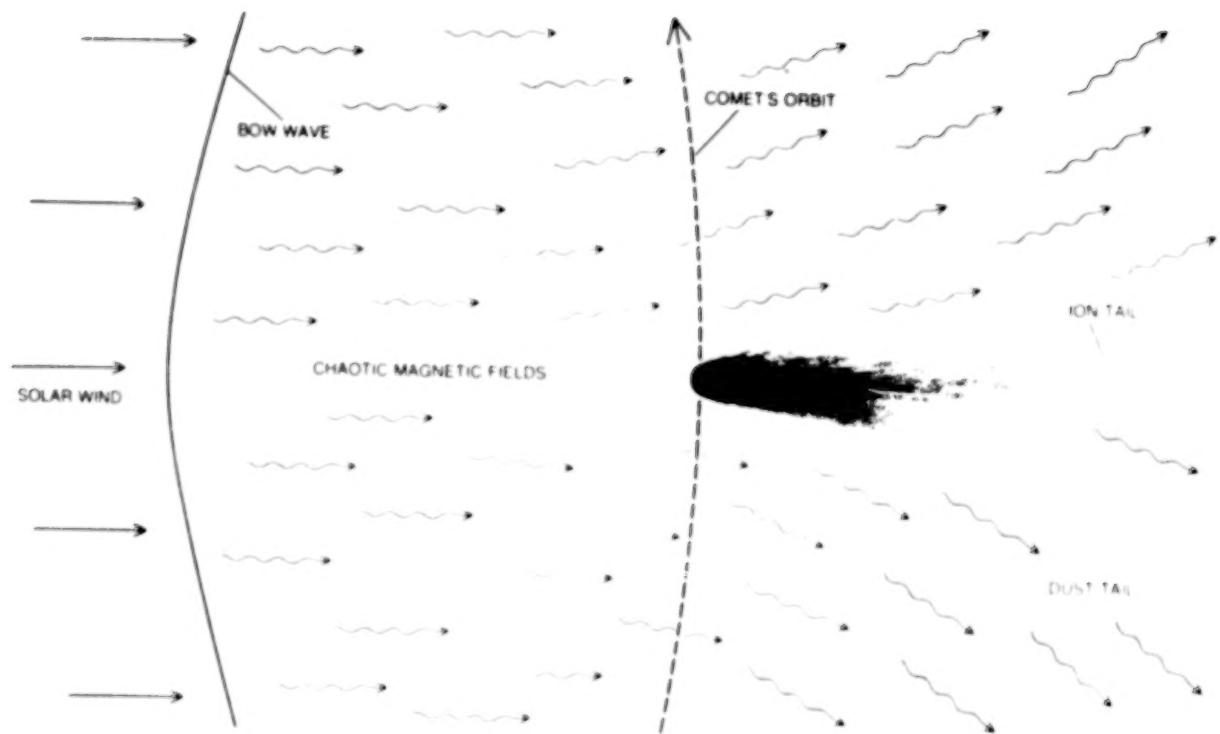
Fig. 6. Sketch of the large-scale features associated with the solar wind.

century, until it was finally understood that the solar wind is the cause of these phenomena.

So we have the nucleus, the cause of it all, only a kilometer to few kilometers in diameter. I think that the comets are the greatest little deceivers in the solar system. A tiny body puts on a magnificent show by ejecting vapor and particles so that the solar radiation reflecting from the particles and being re-radiated from the gases produces a conspicuous comet. A 5 to 10-km diameter body can produce phenomena that stretch out visibly over a hundred million kilometers or more.

Comet Kohoutek, 1973 XII, was a great disappointment for the public, but a huge success for scientists. Figure 7 shows, for example, the twisted nature of the ion tail near the head of comet Kohoutek. In Figure 8 is comet West, 1976 VI. It is an extremely dusty comet, but near the head there is a bit of ion tail up at the top. This looks enormously different from one picture to the next. Figure 9 was taken in blue light and the ion tail shows up much more strongly to the right; the dust is again on the left. Figure 10 shows comet West in the red and therefore accentuates the dust. The striations in the dust tail are quite complicated to explain. They are much like those of 1910 I, the comet in Figure 1.

Now comet West was by no means unique, but relatively rare in that its nucleus split. There are four components showing in Figure 11. These slowly separated. Sekanina discovered a remarkable fact about split comets; those pieces that survive the shortest time are accelerated away from the original orbit with the greatest velocity. Among multiple nuclei in split comets, differential non-gravitational forces arising from the jet action of the sublimating gases control the relative motions.
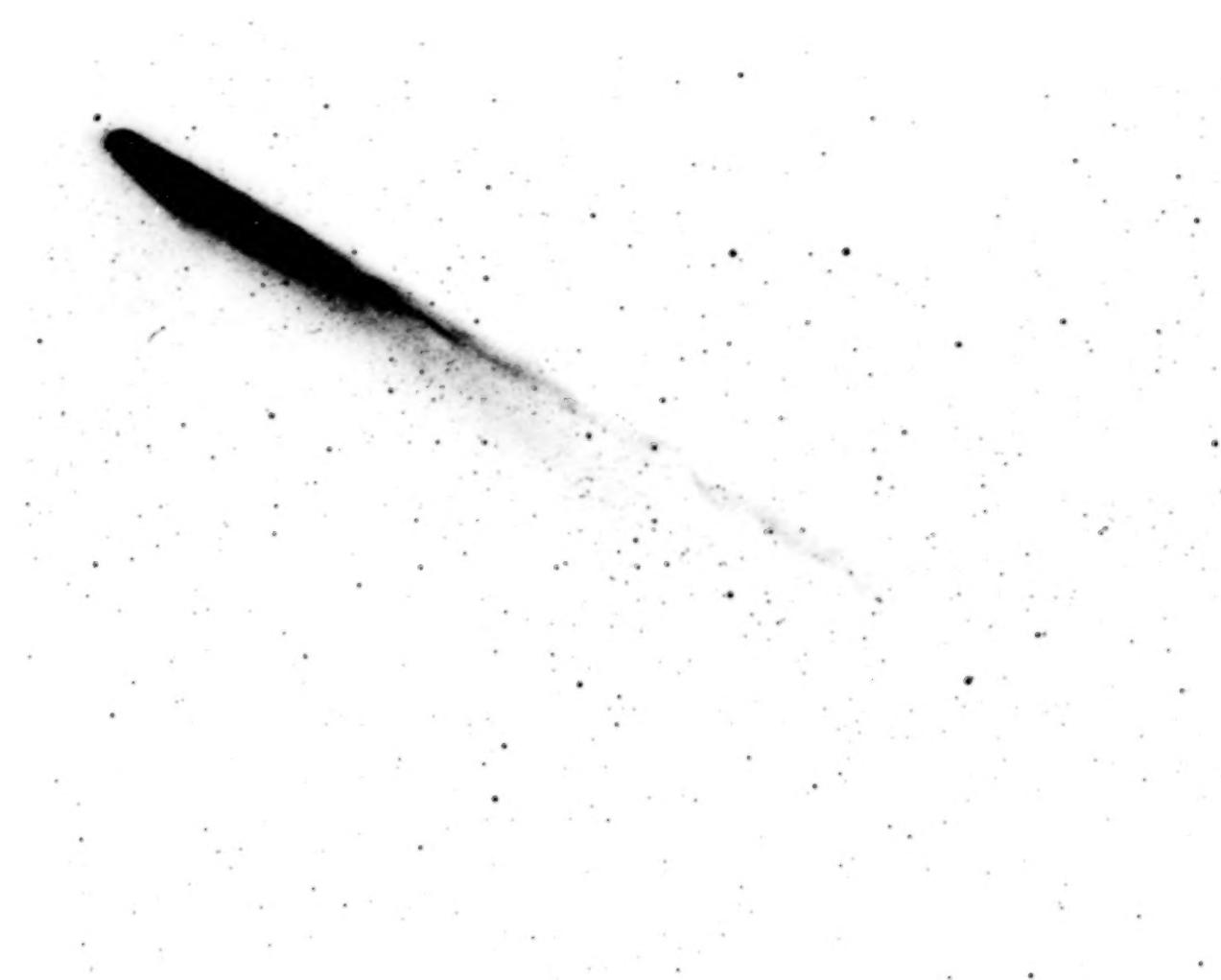
Fig. 7. Comet Kohoutek, 1973 XII.
(Joint Observatory for Cometary
Research photograph)

Fig. 8. Comet West, 1976 VI.

Fig. 9.   Photograph of Comet West (1976 VI)
taken in blue light.

Fig. 10. Photograph of Comet West (1976 VI) taken in red light.

Fig. 11. View of Comet West (1976 VI) after its
nucleus has split into four components.

The sublimating gases cause a small piece to move away at a greater relative velocity than a larger piece, because of the difference in surface-to-mass ratio.

A multiple nucleus will always separate. There is no force adequate to bring the pieces back together again. This, I think, is the most conclusive proof that a long-lasting comet must possess a single coherent nucleus. The observations show, indeed, that most comets do persist for a long time. Most of the short period comets show non-gravitational forces, either acceleration forward in the orbit, increasing the period, or backwards, shortening the period. About equal numbers show period increases or decreases, indicating a random character to polar axis directions. A calculation of the forces shows that the nuclei must be rather small to enable the sublimation, the jet action of escaping gases, to change the orbits perceptibly. Radii of periodic comet nuclei are the order of 1 km.

Figure 12 is my favorite comet picture; it is Comet Kohoutek taken from space. One is in ordinary light and the other is from neutral hydrogen, Lyman-alpha light in the very far ultraviolet undetectable through the Earth's atmosphere. The circle represents the Sun at the distance of the comet to illustrate the size of the neutral hydrogen cloud. Although not the first, this was an exciting verification of Biermann's deduction from my icy comet model. If water is one of the major constituents of a comet, there should be a huge hydrogen cloud. The loss rate of water is on the order of ten tons per second for brighter comets.

Earlier I mentioned the great scientific gains from Comet Kohoutek, due largely from research carried out with the aid of generous support by NASA. They are listed in Table 1. The radio observers first found

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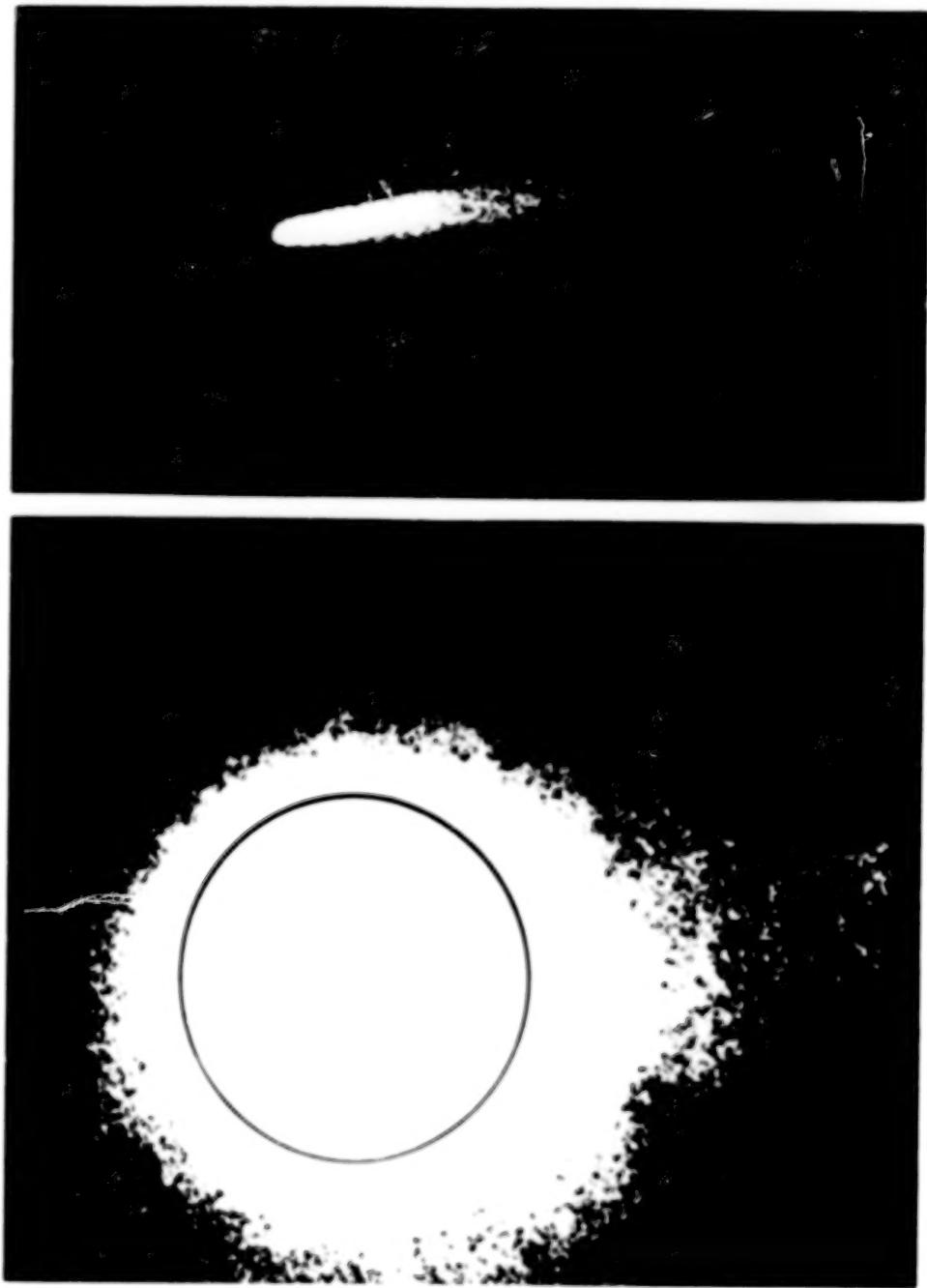
Fig. 12. Comet Kohoutek (1973 XII) as seen from space.
(Top) Photograph in white light. (Bottom)
Photograph in Lyman-alpha radiation. The
circle represents the size of the solar disk.

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TABLE 1

MOLECULES ADDED BY STUDY OF COMET KOHOUTEK (1963 f)

By radio

CH_3CN Methyl Cyanide

HCN Hydrogen Cyanide

also observed OH and CH

By optical

H_2O^+ in tail

By ultraviolet

C and O

By infrared observed

Silicate Band in tail

Not observed

CH_4, Methane

NH_3, Ammonia

Helium

methyl cyanide and hydrogen cyanide and also observed OH and CH, and more recently H_2O. Optically, for the first time, the water molecule was first identified via the H_2O^+ ion while the ultraviolet registered atomic transitions of neutral carbon and oxygen atoms.

In the infrared, the dust particles showed the ten-micron band of silicon, indicating that the particles are, indeed, silicates, as we would expect from meteors. Their nature and size has come more recently from Ney's work; they are usually smaller than one or a few microns and they have a slightly imaginary index of refraction, making them slightly absorbing. In the antitail (dust in the orbit plane seen sunward from the comet), Ney observes that the silicon band is absent, proving that the particles are larger.

Not observed are methane and ammonia which, although difficult to observe, one would expect to be among the primary substances in the comet. We really didn't expect much, if any, helium in comets, but it was looked for and not found.

For the materials in Table 2 I have used the term non-organic although the chemists correct me very quickly. Everything with carbon isn't necessarily organic. In any case the non-carbon material identified in the comets consists basically of the most abundant solar atoms that can form compounds -- hydrogen, nitrogen and oxygen. Near the Sun, at about three quarters of an astronomical unit, sodium shows in cometary spectra. In the sungrazing comets very near the Sun, all the lines appear that you would expect to find from heavier, fairly abundant atoms, such as found in meteorites or meteor spectra. Then, in the ion tails, are N_2^+, OH^+, and the water ion.

In the carbon category (Table 3), we again have quite an array of materials, mostly composed of carbon, nitrogen, oxygen and hydrogen.

TABLE 2

NON-ORGANIC MATTER IN COMETS

$$NH, NH_2, O, OH, H_2O, H$$

Near Sun: Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V

In Tail: N_2^+, OH^+, H_2O^+ and silicate particles

TABLE 3

ORGANIC MATTER IN COMETS

$$C, C_2, C_3, CH, CN, CO$$

$$CH_3CN, HCN, CS$$

AND IN TAIL

$$CH^+, CO^+, CO_2^+$$

Clearly this material makes up the primary icy structure of the comet. We still have this mystery of identifying the parent molecules other than H_2O that produce the observed radicals.

I think Kohoutek, although it was a disappointment to the public, is a remarkable example of how much can be learned by concentrated effort. When everyone is excited and using his best observing techniques, whatever they are, and when all are working cooperatively, the result can be magnificent. We are all very grateful to NASA for the support they gave to that program. It did make it possible for so many observations and so many new results to be obtained from Kohoutek.

The physical structure of comets is still poorly known. The only tangible particles that we believe to come from comets are those collected in high altitude balloons and U-2's by Brownlee and his associates. Figure 13 depicts one of those aggregates from the high atmosphere that come in as micrometeorites. Öpik and I predicted long ago that tiny particles could sneak into the atmosphere without losing too much by heating. Note the one-micron scale at the bottom. The material looks like fish roe of sub-micron particles. I wish we had time to discuss them. They seem to be unique. Robert Walker was saying this morning that everytime you see one of those particles, you can predict what the composition is going to be.

Now a brief word about cometary orbits. Figure 14 shows the orbits of a few of the periodic comets going just beyond Jupiter. I won't persist with this except to say that these comets of short period have been disturbed by the planets, mostly Jupiter, from orbits with periods of millions of years which went out to something like 40,000 astronomical units from the Sun, as shown long ago by Oort. New comets, those that are making their first appearance in the inner solar system, have been proven conclusively by Marsden and his associates to have

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Fig. 13. Photomicrograph of meteoritic
material collected on U-2 flight.
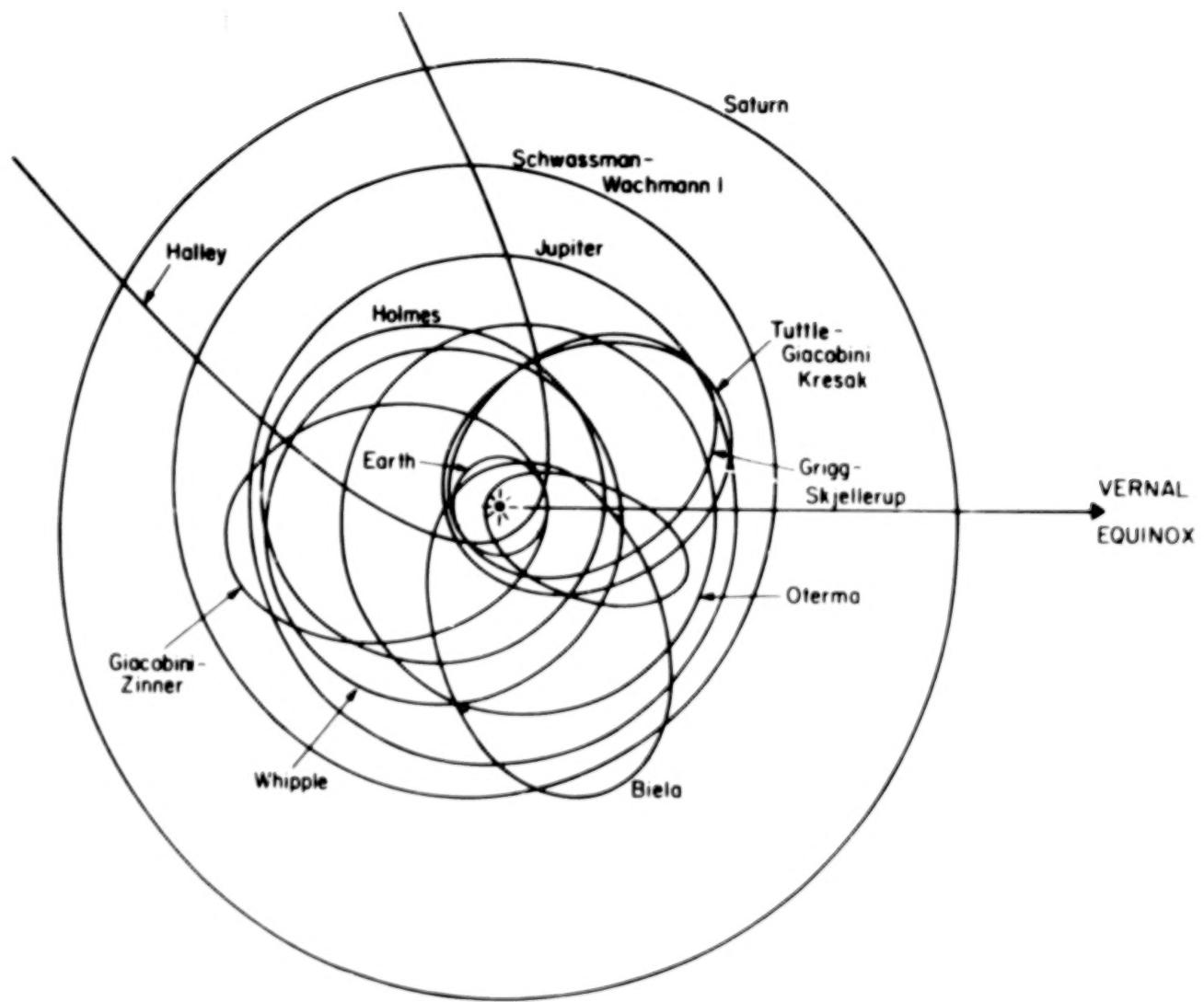
Fig. 14. Orbits of selected short period comets.

Saturn

Schwassman-
Wachmann I

Halley

Jupiter

Holmes

Tuttle-
Giacobini
Kresak

Earth

Grigg-
Skjellerup

VERNAL

EQUINOX

Oterma

Giacobini-
Zinner

Whipple

Biela

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come from such great distances. The questions are: Where did they

originate? How did they get into this great Öpik-Oort cloud which we

know encompasses a solar centered volume of some 40,000 astronomical

units radius?

In Figure 15 we see the great Trifid nebula, typical of many in

interstellar space. They are huge gas-dust aggregates which we now

know to be, indeed, the birth place of stars, clusters of stars, and,

surely, of some solar-type systems. Such great clouds can collapse,

perhaps from gravitational instability alone, perhaps helped by pressures

from very bright stars or supernovae. The Trifid nebula is a beautiful

example of one of these gas-dust, stellar incubators, illuminated by

newly hatched stars.

For discussion let us look at an interpretation (Figures 16a and b)

of the old Laplacian hypothesis. Since nobody has demonstrated a much

better picture, I like these old drawings. The first shows the collaps-

ing cloud and the second shows the planets developing in rings. Now we

know that can't be true, at least directly from the nebula, but never-

theless, we do know that large clouds collapse. They must have great

angular momentum. Therefore, they must develop flattened discs. Perhaps

there actually was a Jupiter ring formed, as Larson suggested from early

calculations.

We find that within Jupiter's orbit the materials of the terrestrial

planets and the asteroids are earthy solids. The temperature must have

been too high for ice to freeze out. When we go out beyond Saturn to

Uranus and Neptune, the mean composition turns out to be just what you

would expect if comets were the building blocks of these great planets.

A much lower temperature would be expected to freeze out ices more

Fig. 15.   The Trifid nebula.

Fig. 16a. Model of Laplacian hypothesis of solar system formation: Collapsing cloud.
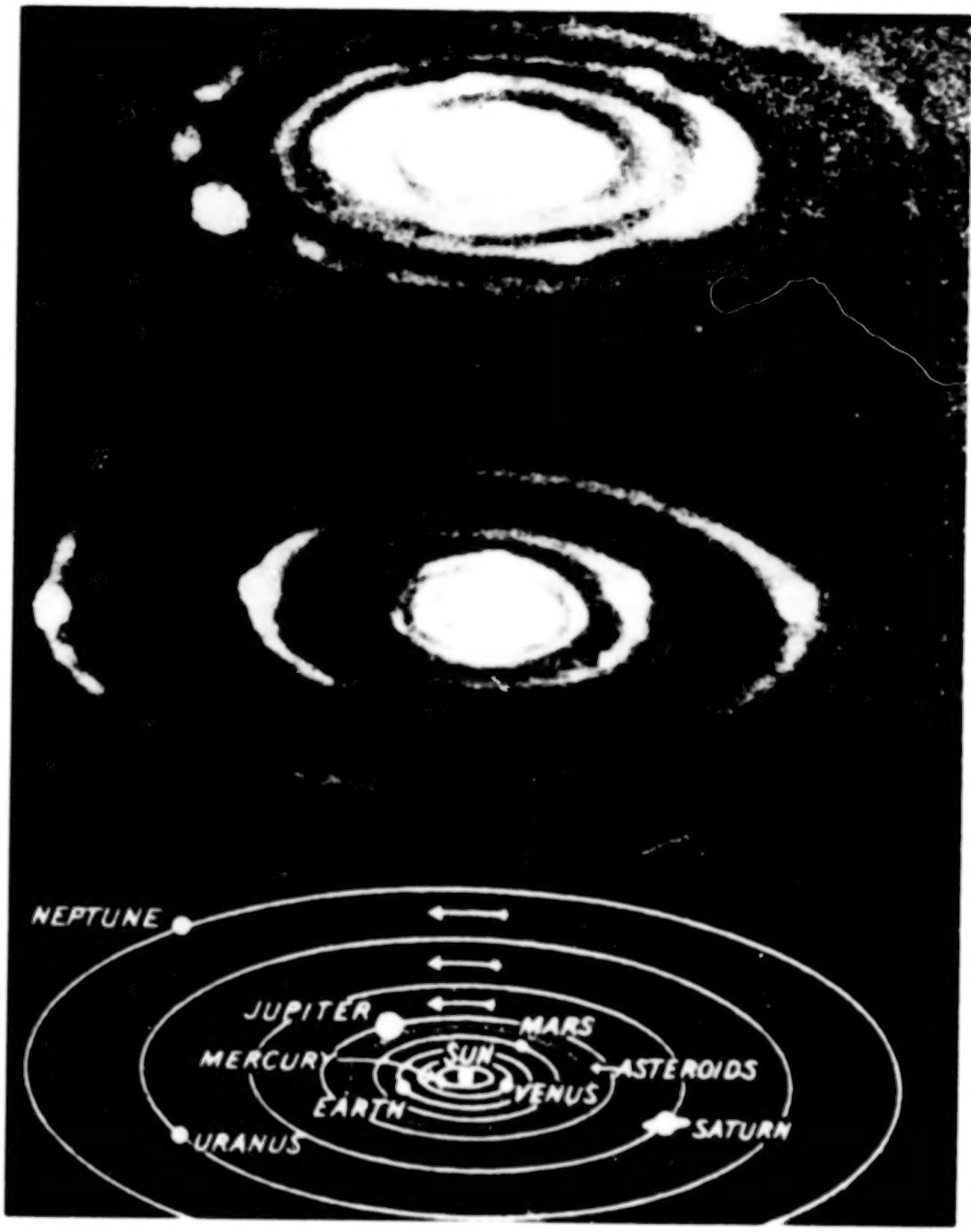
Fig. 16b. Model of Laplacian hypothesis of solar system
formation: Planet development.

volatile than H_2O ice. I hope the missions to Uranus will give us the J_2 terms and other terms describing the distribution of mass with respect to the equator of Uranus so that we can learn more about the internal structure. At present, within the accuracy of the theory, the composition is almost exactly that of a frozen mix of solar material, about 98 percent hydrogen and helium, with carbon, nitrogen, oxygen, and heavier atoms as contaminants, retaining only the compounds that would freeze out at 50 to 80 K or at a somewhat lower temperature -- comets for all practical purposes.

If the inner planets, the terrestrial planets, are made up of planetesimals, then Uranus and Neptune are made of what I like to call cometesimals, dirty ice masses up to small and large comets. The question remains as to whether or not Uranus and Neptune formed first and then threw the remaining comets into bigger and bigger orbits by gravitational interactions. Öpik has done a number of important calculations on this problem.

As an alternative, Cameron is now suggesting that the Sun and the planets all formed concurrently in time. The entire system shrank as the Sun's increasing mass reduced the orbits of the growing planets. The solar nebula was quite massive. Finally mass was thrown out very quickly leaving comets in larger orbits because of the reduced central mass. The ejection took place in a fraction of a period for comets which were several hundreds of astronomical units from the Sun. Thus the distant comets were thrown into extremely elongated orbits that constitute the Öpik-Oort cloud.

In any case, I think we can say without any question that comet-like bodies, whether or not they are represented exactly by the comets we see

today, were, indeed, the source of the outer planetary system. They were the building blocks beyond Saturn. They are the most fundamental material we know of, left over in the construction of the solar system. I believe the comets we see today are representative of this material, which must have amounted originally to hundreds of earth masses; we do not know how much. Certainly comets contributed significantly to Saturn. Saturn contains more of this type of material than Jupiter, which is nearer to a pure solar mix.

Much evidence points to the Earth's having lost its primitive atmosphere, requiring a later replacement. Some people believe the volatiles came from within. Possibly they came from comets. Suppose that the solar nebula was removed quickly and that there were a great many comets. I have suggested, but not yet proven, that they could have formed a temporary cometary nebula inside the orbit of Jupiter. This nebula could have contributed the volatiles to the Earth and quite possibly also the atmospheres of the other terrestrial planets. The only supporting evidence we have at the moment can also be explained in other ways. It is the lack of the light noble gases. We do not expect noble gases to be abundant in comets unless the temperatures were unbelievably low, freezing the gases. Knowledge of the basic elemental chemistry of comets will answer the question.

The chemistry and the physical structure of comets, including isotopic studies will be highly desirable to answer other questions such as the oxygen anomaly, the oxygen 16, 17, and 18 ratios, as Clayton has discussed, and the carbon 13 and 12 ratios. The studies of these materials will tell us much about how the comets originated.

Now a word about the philosophy of the study of comets. In mission planning there is a tendency to say that the study of the

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phenomena should play a secondary role as distinguished from the study of the nucleus and the actual matter in the comet. I dislike this philosophy because the phenomena themselves, such as the plasma physics, do tell us something about the nature of the material. In planning cometary research, I do not think one should properly distinguish between the phenomena and the body itself, the nucleus of the comet, any more than in the study of the human body one should separate the mind and nervous system from the chemistry of the physical body. They are all a part of the same grand problem. Anything new learned about the phenomena is important in understanding the nature and orgin of comets.

The rotation of comets, for example, may not be a basic property indicative of the original conditions, because it can be induced by jet action. Nevertheless, rotation is important to study. We know the periods, possibly, of two comets. My current work on P/Schwassmann-Wachmann 1 places its period at just about five days and gives the orientation of the pole. Recently, Fay and Wisniewsky have photometrically found a period of about five hours for P/D'Arrest, but not the polar orientation. Of 34 comets, about half are turning retrograde and half prograde.

The study of the phenomena of distant comets such as P/Schwassmann-Wachmann 1 provides considerable evidence that much cometary material is in an amorphous icy state. When cometary material is heated to a relatively low temperature, somewhat over 100 K, copious sublimation occurs. I find evidence also that a crust forms, suggesting cementing action by heat, even at these low temperatures. This seems to happen in comets generally.

Finally, in summary, the study of comets, particularly space missions to comets, provides the opportunity to learn a great deal about the sequence of events that led to their formation and will provide major clues about the formation of our solar system. We should be able to learn how volatiles arrived on the Earth and, indeed, the basis for the existence of life on the Earth.

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CONNECTIONS BETWEEN COMETS AND PLASMAS IN SPACE

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From the point of view of plasma physics, comets are unique and
fascinating objects. Many fundamental aspects of cometary structure and
dynamics are known to involve plasma processes, but in a large number of
areas the basic mechanisms are poorly understood. It seems certain that
many of these basic questions about comets will remain open until detailed
in situ measurements are available. In terms of general plasma physics,
it also seems certain that we will learn much by achieving such detailed
understanding of comets, since many of the dynamical processes in the
cometary system represent unusual examples of very important, widespread
natural phenomena.

I would like to confine attention here to four general areas involving
comets and plasma physics. These are:

1. The comet as an obstacle in the solar wind,

2. The nature of the plasma flow,

3. Collisionless shocks,

4. Plasma processes in the comet tail.

In terms of the first of these topics, it has been known for many years
that the comet-solar wind interaction is very different in character from
the wind interaction with other objects. The bottom part of Figure 1, which
is similar to a drawing shown earlier by Dr. Whipple, depicts a widely
accepted concept of the comet-wind interaction in terms of development of a
contact discontinuity and an upstream collisionless shock. One point that
is highly unusual here concerns the scale of the system, since along the
sun-nucleus line the contact surface is at $r = 10^5$ km, even though the
nucleus itself is presumably only a few kilometers across.

The scale values were derived many years ago by Biermann et al. (1967),
and the top panel in Figure 1 shows one of their numerical examples.
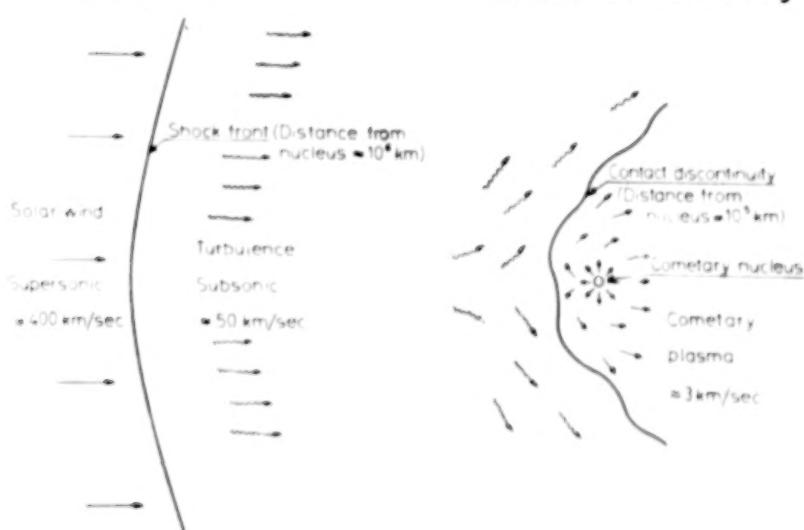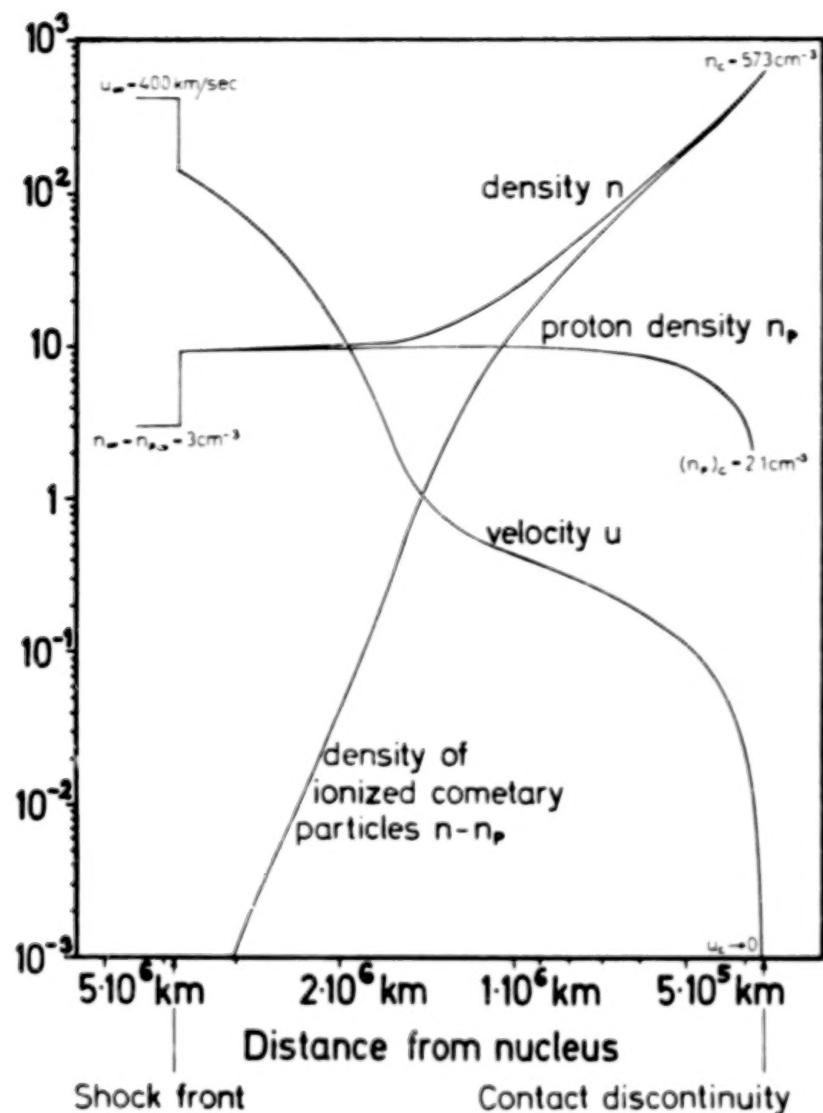
Fig. 1. (Bottom) Configuration of plasma interaction of solar wind with a comet. (Top) Calculated velocity and density profiles upstream of a comet.

calculated using a simplified comet model. One basic point that is unusual has to do with the very low gravity of the nucleus and the associated large scale height. A related feature involves the very large extent of the neutral gas cloud, which leads to continuous production of newly-ionized cometary particles at huge distances from the source. These effects lead to a very gradual decline in plasma density over an enormous distance from the nucleus, and this yields the expected large scale for the comet-wind interaction, as shown in Figure 1.

The top part of Figure 2, taken from the Comet Halley Science Working Group report, shows more details of the expected wind-comet interaction, including the development of an extended plasma tail, and the presence of a very large neutral hydrogen corona. In order to fit all of these important cometary elements on a single drawing, it is necessary to use a logarithmic distance scale, as indicated here. Of course, the logarithmic distance scale does tend to obscure many important and unusual characteristics of the comet-wind interaction. For instance, it must be noted that the outermost H-corona contour shown here passes through the sub-solar point at a radius of about 4×10^7 km 0.25 A.U. Moreover, this sketch indicates a shock-to-contact surface subsolar standoff ratio of about $(2 \times 10^6/10^4) \approx 200$, but it obscures the fact that this differs greatly from the conventional fluid-dynamics results which leads to a ratio of 1.4. In order to put all of this in a proper perspective, the bottom panels of Figure 2 show corresponding details of the Earth-wind and Venus-wind interactions on the same relatively unfamiliar logarithmic distance scale. It is apparent in the lower panels that the shock forms at a distance that is only 40 percent upstream from the subsolar obstacle distance (magnetopause or ionopause), and that the obstacle itself has a dimension that is comparable (within an
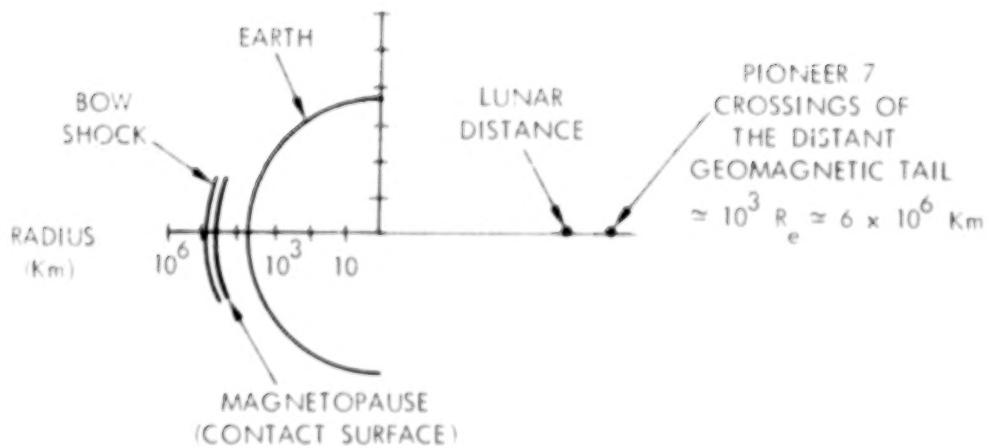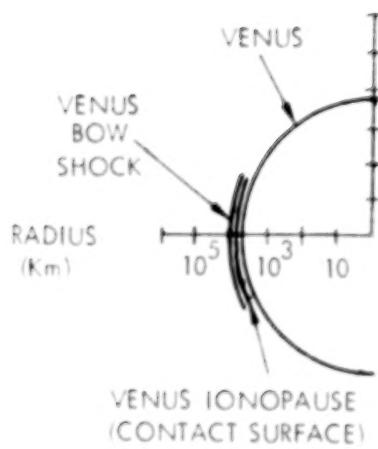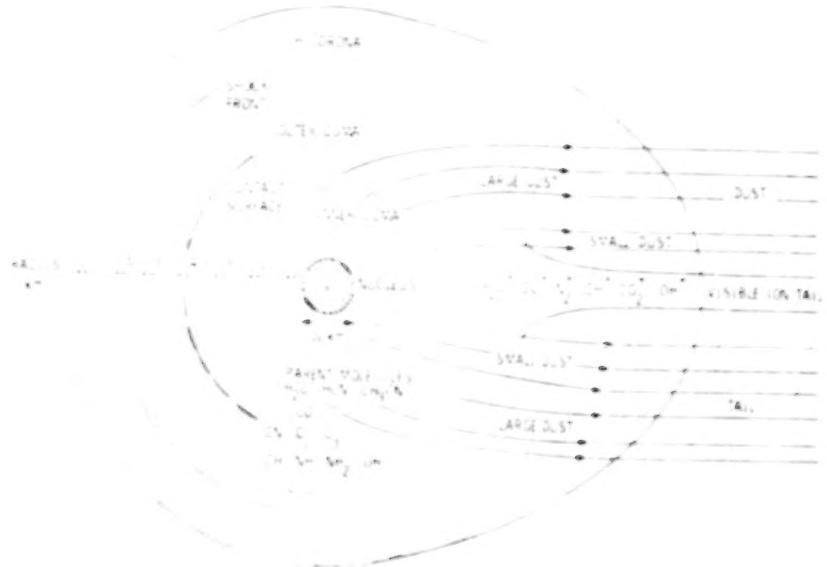
Fig. 2. (Top) Sketch, on a logarithmic scale, of the several
regions of the comet-solar wind interaction. (Bottom)
Similar logarithmic sketches of the solar-wind inter-
action processes at Venus and Earth.

order of magnitude) to that of the parent body, in great contrast with the case for the comet. Moreover, the Pioneer-7 information concerning the extent of the Earth's tail shows that the comet tail also has an exceptional length. Recently Intriligator et al. (1977) discussed Pioneer-7 data in the anti-solar region at 3000 R_e and showed that tail-related changes in the plasma parameters were measured just beyond the point shown in Figure 2. However, since plasma tails for comets are extremely easy to detect, we know that the cometary structures generally do have huge scales, as indicated at the top of Figure 2.

There is no corresponding firm information, from optical or other remote sensing observations, on the position of the contact surface and bow shock, and there is really no firm knowledge that a well defined shock exists. What we do know is that the H-corona spills out in all directions so that a large population of neutrals from the comet atmosphere will be present in the upstream solar wind. Figure 3, taken from a forthcoming paper by Lillie (1978) shows a photograph of Comet Bennett with superimposed hydrogen intensity contours derived from the University of Colorado ultraviolet instrument on OGO 5. The existence of this huge cloud of neutrals in the upstream region leads to some real uncertainty about the formation and physics of the comet bow shock. Wallis (1973) pointed out that when the neutrals are ionized in the upstream region, these "newly-born" ions are picked up by the solar wind. The high-mass upstream ions then load down the incoming solar wind, and this mass loading can ultimately lead to subsonic flow, which does not produce any collisionless shock at all. Thus, Wallis questioned the conventional assumption that a bow shock forms upstream from the comet. Similar questions have been raised about the wind-Venus interaction, but since the comet gravity is so low, the

Fig. 3.   Lyman-alpha brightness contours superimposed on
          a photograph of Comet Bennett.   (After Lillie)

comet-wind interaction is the one most likely to lead to a thick, neutral-dominated interaction of this type.

This uncertainty concerning the cometary bow shock is only one of many open questions involving plasma flows. Figure 4, taken from a paper by Wallis and Dryer (1976), illustrates many of the flow regimes that are possible in the neighborhood of the comet. Table 1 defines the different regions identified in the figure. One very novel flow configuration is indicated here. Specifically, Wallis and Dryer pointed out that the tail-ward flow, which is initially subsonic and sub-Alfvénic, may involve formation of an internal shock at the interface with the supersonic wake. This type of internal shock has recently been discussed in terms of radial outflow models for the Jovian magnetosphere (Kennel and Coroniti, 1975), and it is interesting to speculate that studies of flows around comets may provide direct information on plasma systems dominated by internal energy sources.

The large-scale dynamical phenomena that develop in the ion or plasma tails of comets are known to be controlled to a large extent by microscopic plasma physics processes, and some of the more important areas of investigation are summarized in Table 2. Figure 5, taken from a paper by Niedner and Brandt (1978) vividly illustrates the great complexity and variety of the large scale spatial and temporal variations detected in comet tails. The figure shows Comets Borrelly (upper left), Halley (upper right and lower left), and Bennett again (lower right). It is clear from these photographs that the plasma tails exhibit significant spatial non-uniformities. When the large scale of the comet tail and the relatively slow speed of the solar wind are taken into account, it also becomes clear that local conditions in comet tails exhibit rapid variations with time.
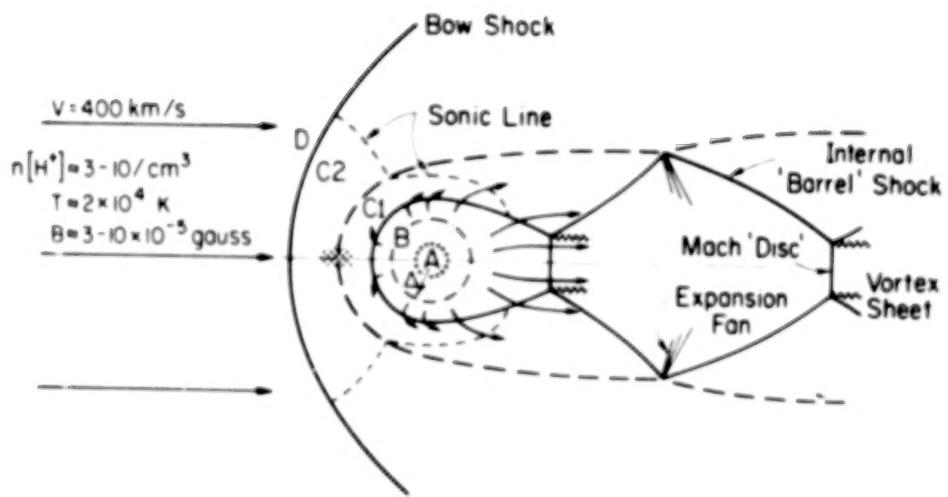
Fig. 4. Wallis and Dryer's (1976) postulated configuration of comet-solar wind interaction processes.

Table 1. Possible Flow Regions Upstream of the Control Source (from Wallis and Dryer, 1976)

Flow Regime	Transition	Comet/Solar Wind
A. Subsonic source flow		Drag and heating of dust; evaporation of icy grains
	Continuous, within a few source radii	
B. Supersonic radial expansion		Photodissociative heating of gas Ionization + cooling + recombination $P_{stag} \approx r^{-1}$, large but finite M
	Shock, where $P_{stag} = O(P_\infty)$	
C1. Subsonic interior plasma		Enhanced cooling gives a denser and narrower region
	Contact discontinuity (perhaps flute or Kelvin-Helmholz unstable)	
C2. Subsonic exterior plasma		Wide region controlled by mass addition and cooling of new suprathermal ions
	Bow shock	
D. Supersonic (-Alfvénic) streaming		Mass addition reduces effective mach number to M ≲ 2

Table 2.   Plasma Processes in Comet Tails

RECONNECTION OF MAGNETIC FIELD LINES

        Stability of X-nulls; tail disconnection; particle acceleration in

        "fireball" regions; substorm analogs

DEVELOPMENT OF INTERNAL TAIL INSTABILITIES

        Onset of filaments, rays, helical structures; viscous interactions at

        the tail boundaries; "amplification" of the piled-up interplanetary

        magnetic field, current-driven discharges, and ionization enhancements

        (anomalous resistivity)

LARGE SCALE DYNAMICS AND VARYING INTERPLANETARY CONDITIONS

        Plasma tail disconnection and sector boundaries; changes in tail

        orientation ("windsock"); possible "flareup" in association with

        interplanetary blast waves

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Fig. 5.   Photographs of Comets 1903 IV Borrelly on July 24, 1903 (upper left),
1910 II Halley on May 13 and June 6, 1910 (upper right and lower left),
and 1970 II Bennett on April 4, 1970 (lower right).   The 1903 IV and
June 6, 1910 photographs of 1910 II are Yerkes Observatory photos.
The May 13, 1910 photograph of 1910 II is from Lowell Observatory and
the 1970 II photograph is from K. Lübeck at Hamburg Observatory.

This conclusion should not be very surprising because our present understanding of the Earth's magnetic tail (which was initially conceived to be similar to the tail of a comet) shows that the tail and the plasma sheet are intrinsically non-uniform and non-steady. Figure 6, taken from a recent review by Russell (1976), shows a snapshot of the inhomogeneous structure of the tail (left side), and an idealized sketch of the anticipated large scale temporal changes that are thought to develop during various phases of a substorm (right side). The types of local measurements that lead to these general models are indicated in the next few figures. Figure 7 shows how intense, low-frequency magnetic turbulence levels are detected in association with high proton flow velocities near the neutral sheet in the Earth's tail (Coroniti et al., 1977), and Figure 8 shows Frank's (1976) idealization of the magnetotail "fireball" model, in which field annihilation at an X-type null provides the source of streaming energy for protons. The fireball and the field reconnection mechanism are not completely understood at present, but it is clear that plasma acceleration does occur in the Earth's magnetotail, that the process is a very fundamental one, and that it is associated with large-scale dynamical changes in the entire magnetosphere.

Figure 9 shows other aspects of IMP-7 and -8 magnetotail plasma probe measurements that are indicative of different local acceleration processes. Frank et al. (1976) detected energetic oxygen ions in the distant tail, and they speculated that the appearance of O^+ ions in this region is associated with the acceleration mechanism for those precipitating auroral electrons known as "inverted V" events. All of these plasma acceleration processes in the Earth's magnetosphere may have cometary
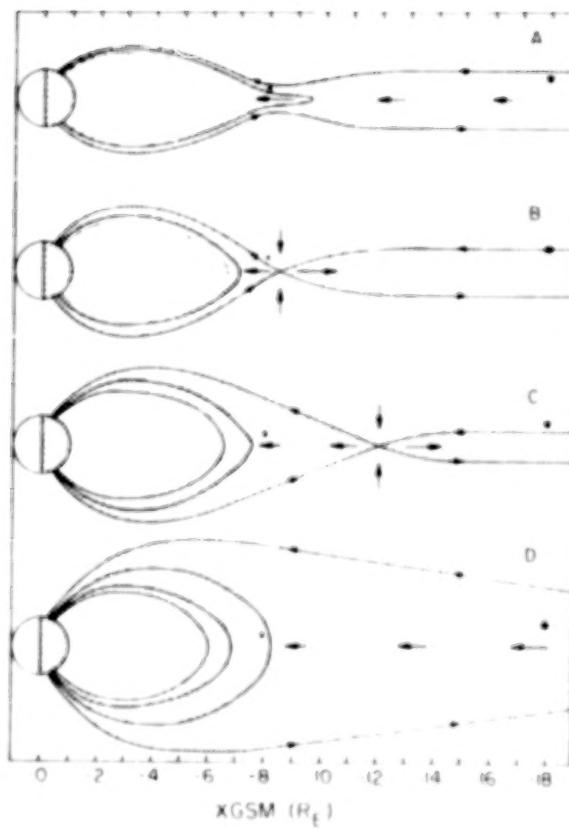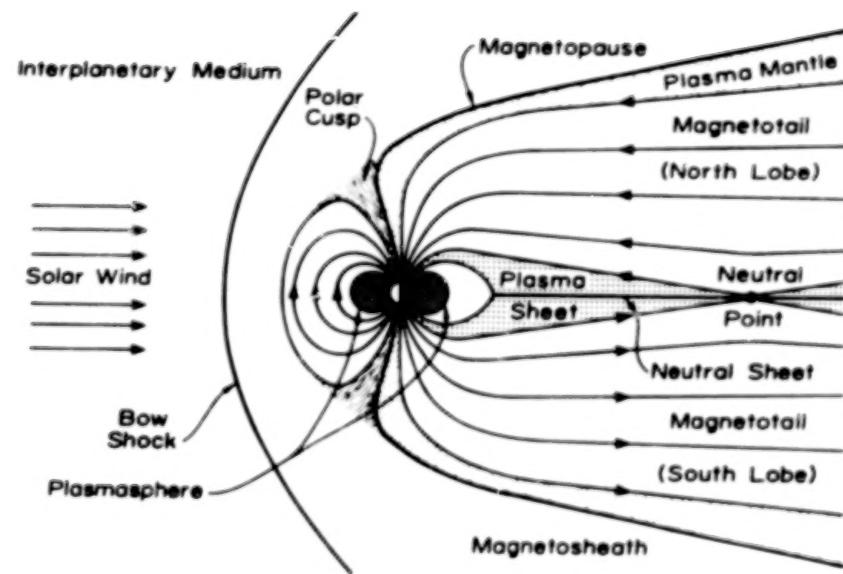
Fig. 6. (Left) Noon-midnight meridional cross-section of the magnetosphere. (Right) Conceptual model of the initiation of the expansion phase and recovery phase of substorms in which a neutral point is formed near the Earth and then recedes. (From Russell, 1976)
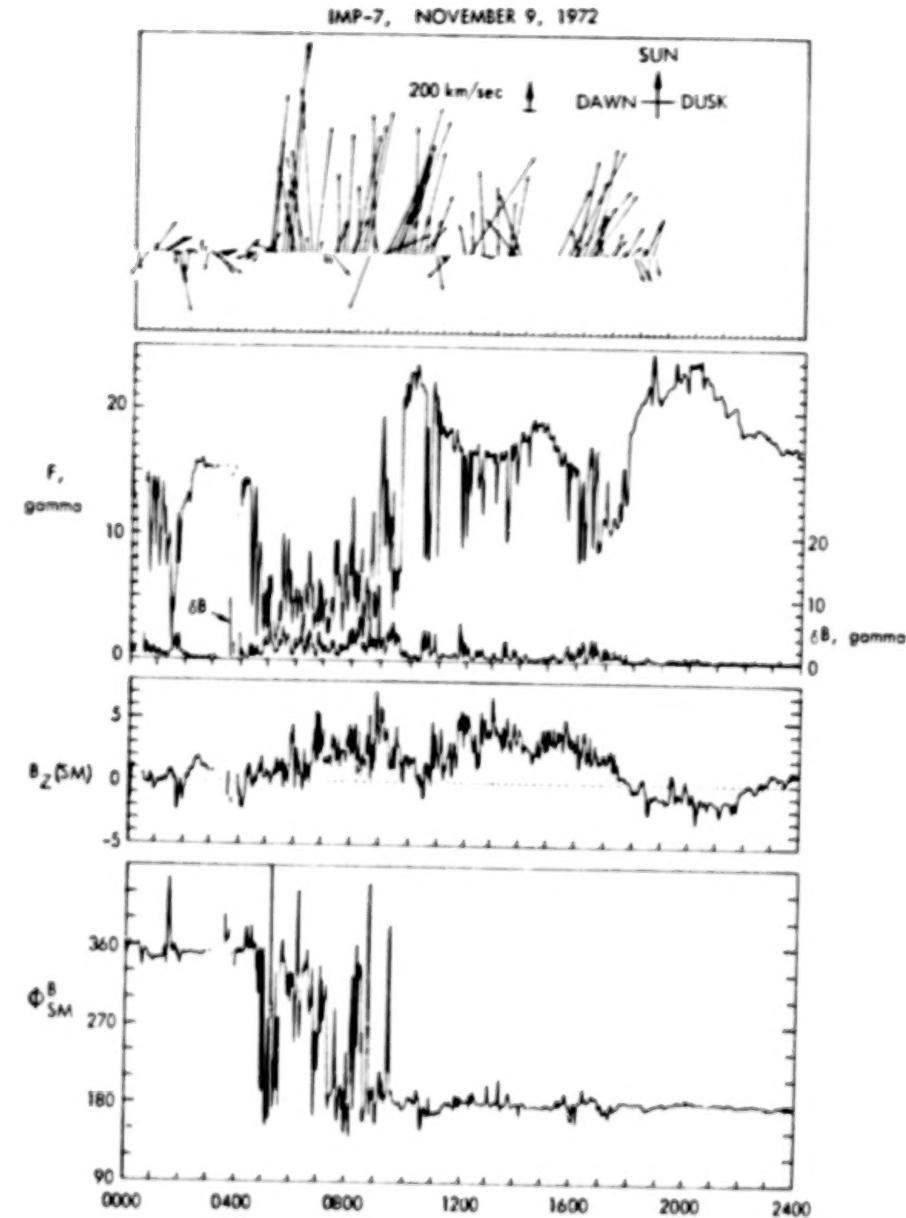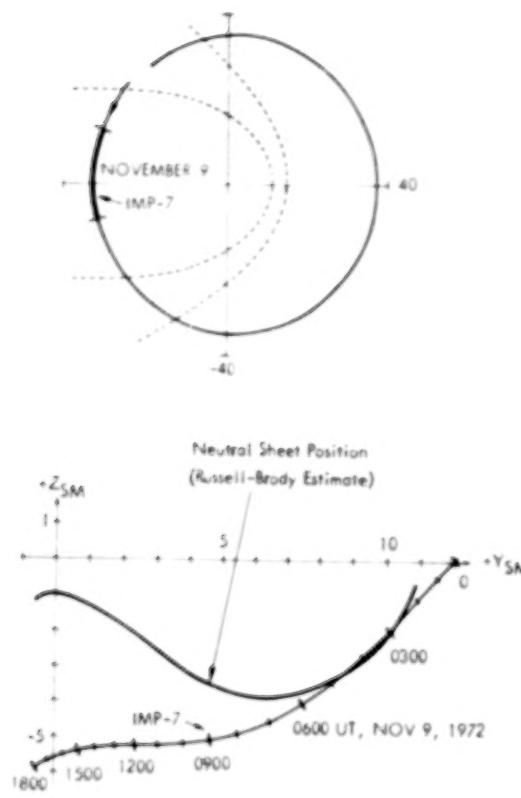
Fig. 7. (Left) The IMP-7 location in the geomagnetic tail. (Right, from top to bottom) The plasma flow velocity vector, the magnitude and disturbance level of the magnetic field, and north-south component of the magnetic field, and the equatorial angle of the magnetic field during a period of intense turbulence observed in the geomagnetic tail by IMP 7.

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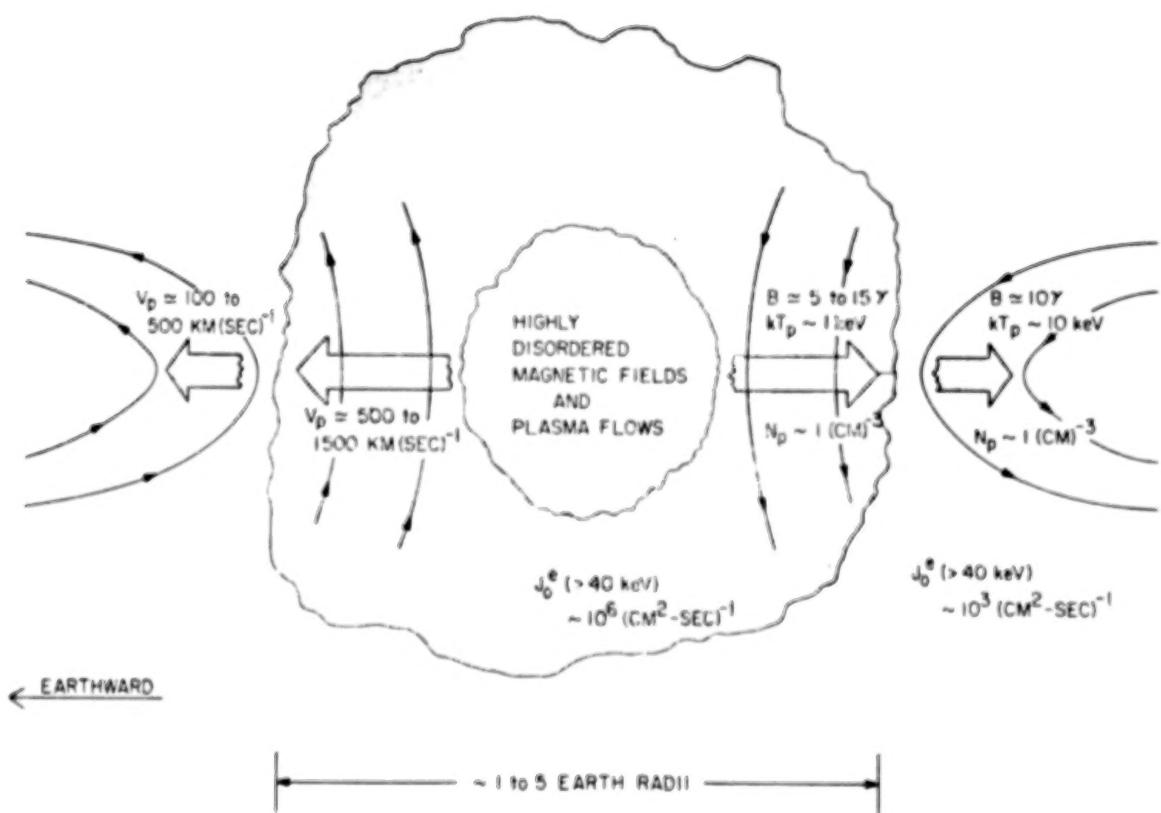
Fig. 8. Frank et al.'s (1976) model of a magnetotail "fireball."
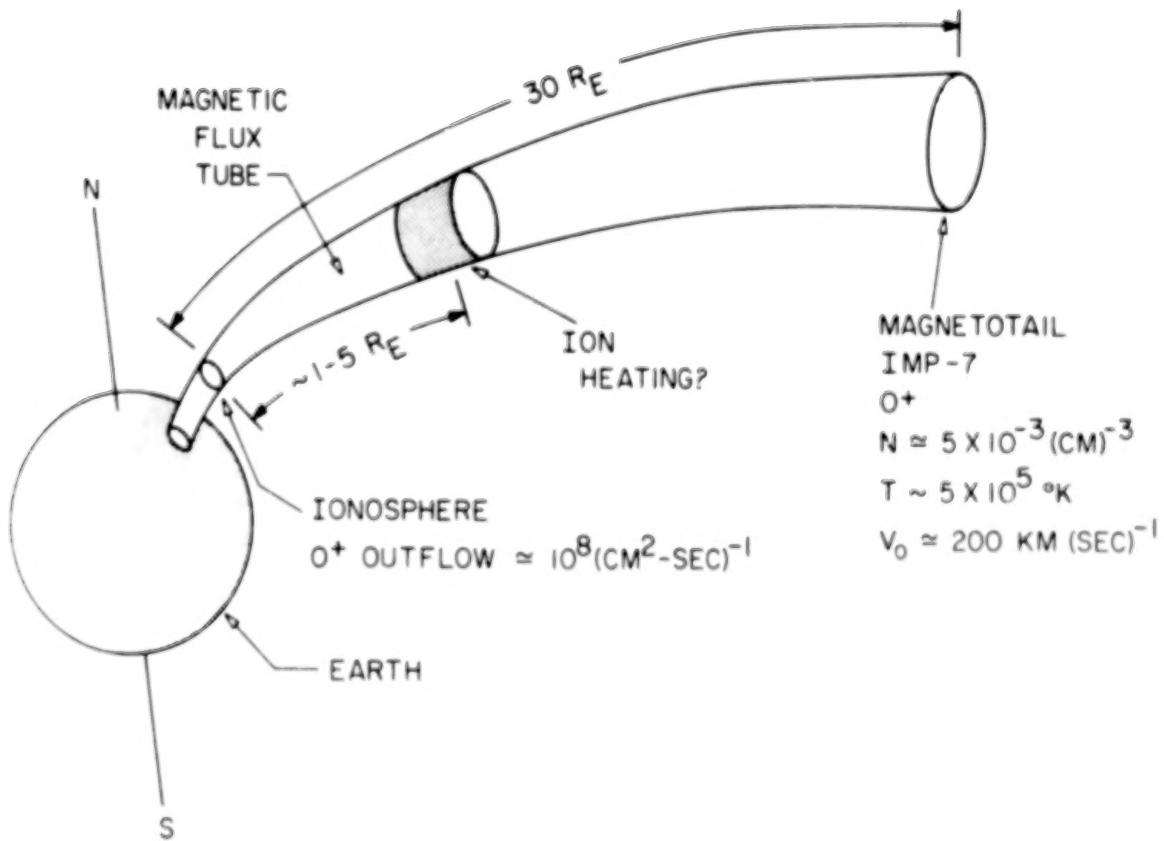
Fig. 9. Model of ion acceleration associated with auroral phenomena. (From Frank et al., 1977)

analogs since cometary "outbursts" or "discharges" are thought to have origins related to substorms and aurora on Earth (Ip and Mendis, 1976).

By now it should be apparent that the data displays involving the geomagnetic tail are primarily concerned with the region fairly close to Earth. These regions, where "fireballs" have been detected, are certainly very important and very interesting, but in terms of the scale of a comet, the IMP-7 and -8 measurements are scarcely in the tail at all. The Pioneer-7 and -8 deep space probes did yield a few crossings of the distant geomagnetic tail, as shown in the top panel of Figure 10 (Intriligator et al., 1969), during which plasma probes measured very rapid changes in the distribution functions, as shown in the bottom of Figure 10. However, it has never been clear whether or not these plasma variations represented spatial or temporal changes, or whether they were associated with internal plasma instabilities or changes in the solar wind itself.

Of course, the geomagnetic tail is not luminous, and we can only carry out multiple point measurements with an expensive array of spacecraft observing platforms. However, the natural luminosity of a comet tail provides an exceptional opportunity to study the dynamics of an enormous plasma "column," and to separate spatial and temporal variations, as well as to distinguish changes driven by solar-wind fluctuations from those associated with local instabilities.

An example of the possibilities is shown in Figure 11. Notice the large "bend" in the comet's tail (Brandt and Rothe, 1976). Niedner et al. (1978) tested the wind-sock theory of comet tails by relating changes in solar wind properties (measured on IMP 8) to this large-scale
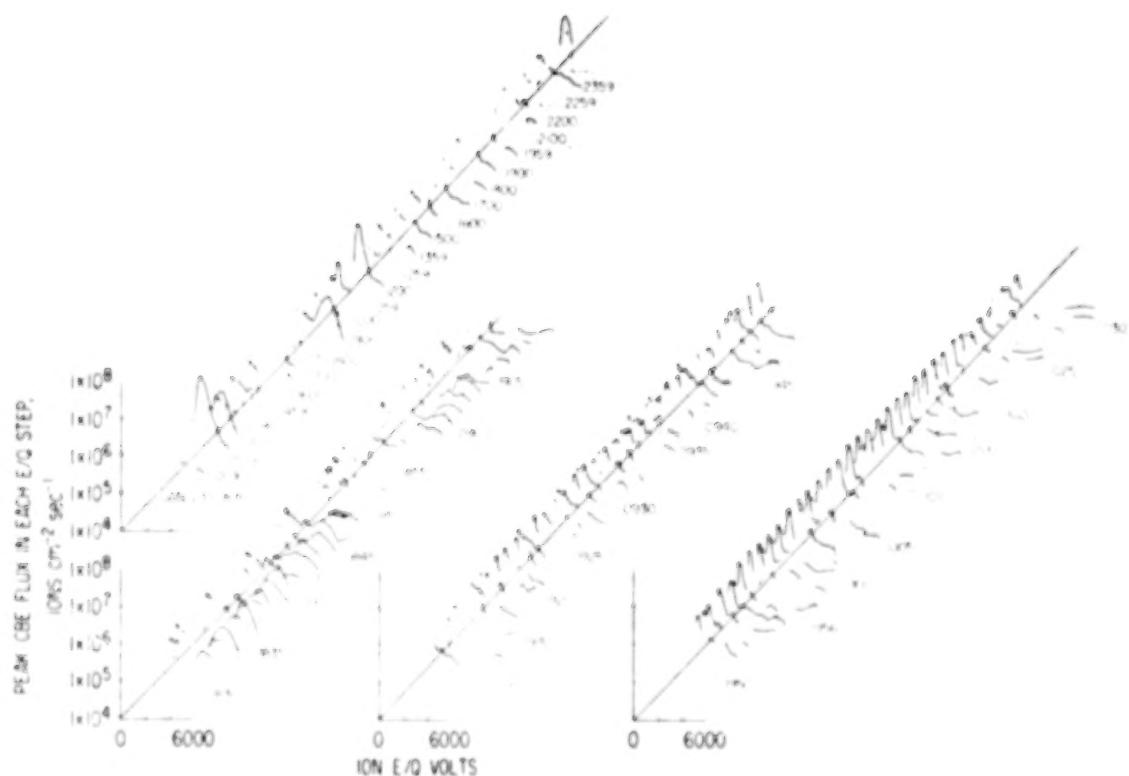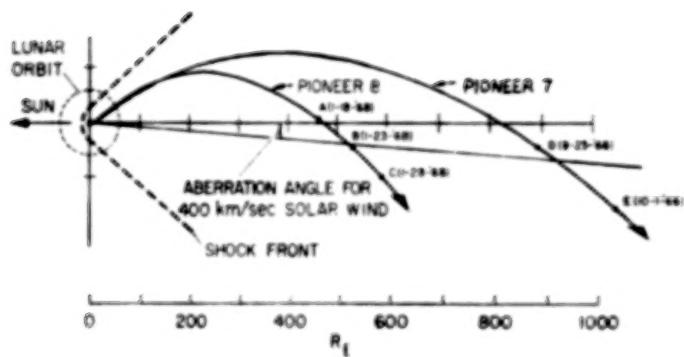
Fig. 10.   (Top) Ecliptic projection of trajectories of Pioneers 7
            and 8.   (Bottom) Ion spectra in the geomagnetic wake
            observed by Pioneer 8 on January 23, 1968.

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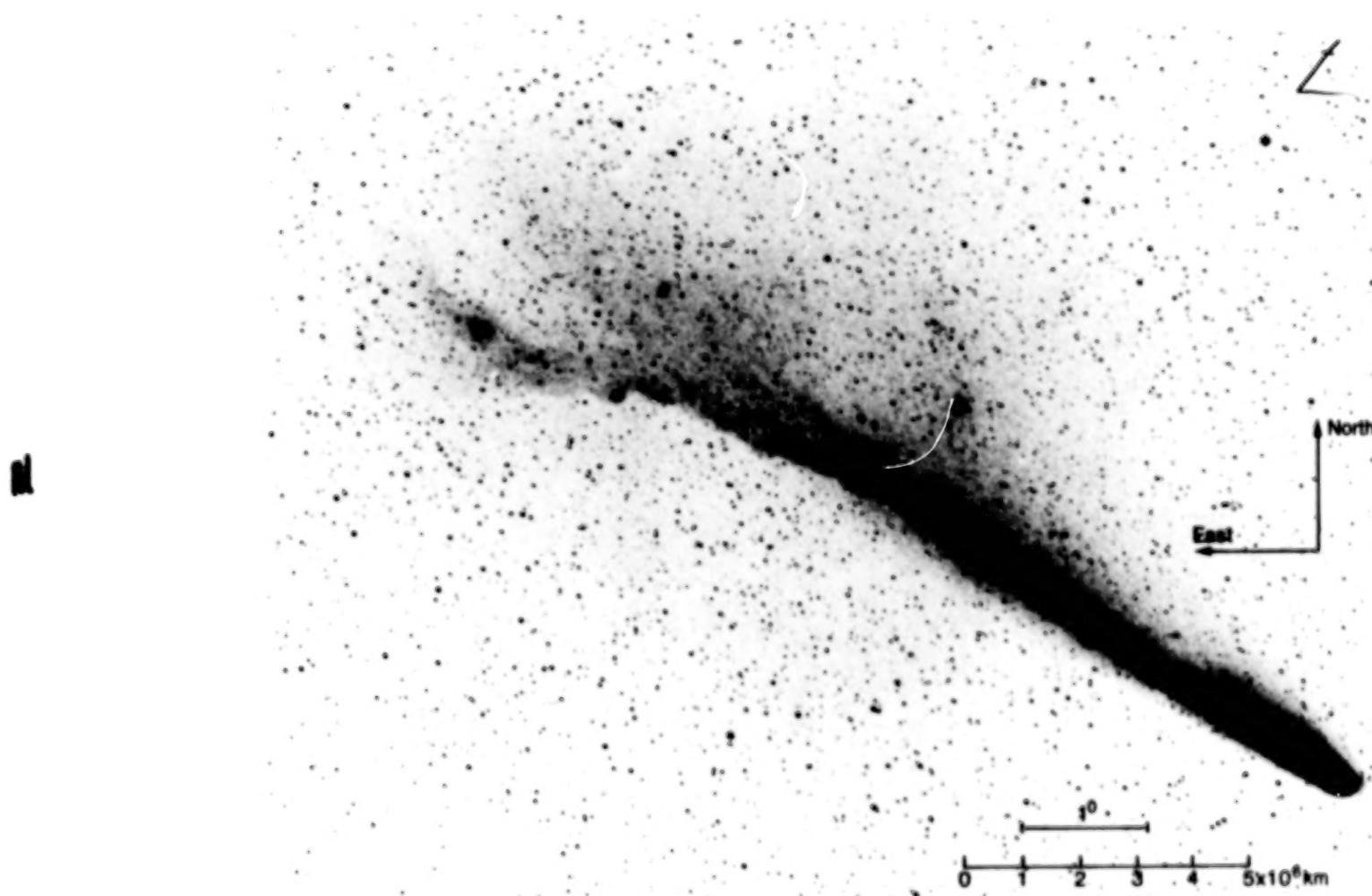
Fig. 11.   JOCR photograph of Comet Kohoutek on January 20, 1974.

disturbance in tail direction. Excellent agreement was obtained. It seems that comet tails are very effective and sensitive probes of changing conditions in the interplanetary plasma.

Niedner and Brandt (1978) also demonstrated that extremely important an' ..iting plasma physics, involving magnetic field merging, reconnection, and "disconnection" can be uniquely studied in cometary ion tails. Figure 12 shows the fundamental points, which are based on the concept that the interplanetary mangetic field is "hung up" in the ionosphere of the comet. For a given interplanetary field orientation, this piled-up field becomes extended and it drapes around the comet to form a plasma tail, as shown in the upper left panel. The concept of "disconnection" is associated with the fact that the p led up field orientation must change if the interplanetary field orientation changes. Thus an advancing null field, such as the sector boundary indicated here, will induce a momentary null in the piled-up field, the existing tail will become disconnected, it will move off in the anti-solar direction as shown, and a new tail with opposite field orientation will form. Figure 13, taken from the paper by Niedner and Brandt (1978), shows an example of the formation of a severed or disconnected tail for Comet Morehouse; the top photograph was taken at 20^h57^m GMT on September 30, 1908 and the lower one at 19^h43^m GMT on October 1. Niedner and Brandt analyzed a number of other cases (including the tail structural changes shown in Figure 5) and they presented convincing evidence for magnetic field line reconnection in response to sector boundaries. When remote sensing observations of this type are combined with in situ measurements, it is clear that comet studies will provide new fundamental information on the field annihilation mechanism.
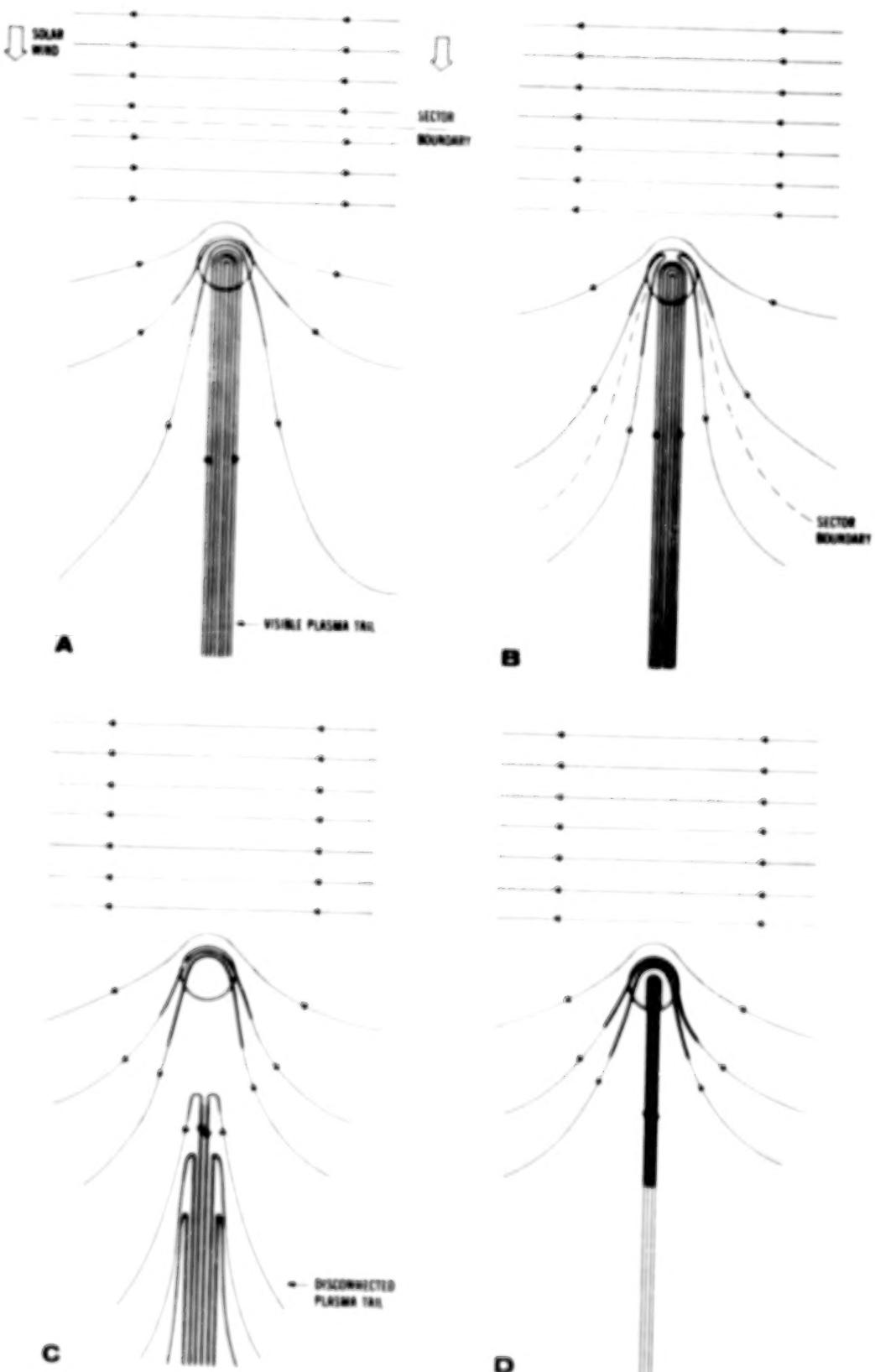
Fig. 12. Process of disconnection of a comet tail in response to the passage of an interplanetary sector boundary. (From Niedner and Brandt, 1978)
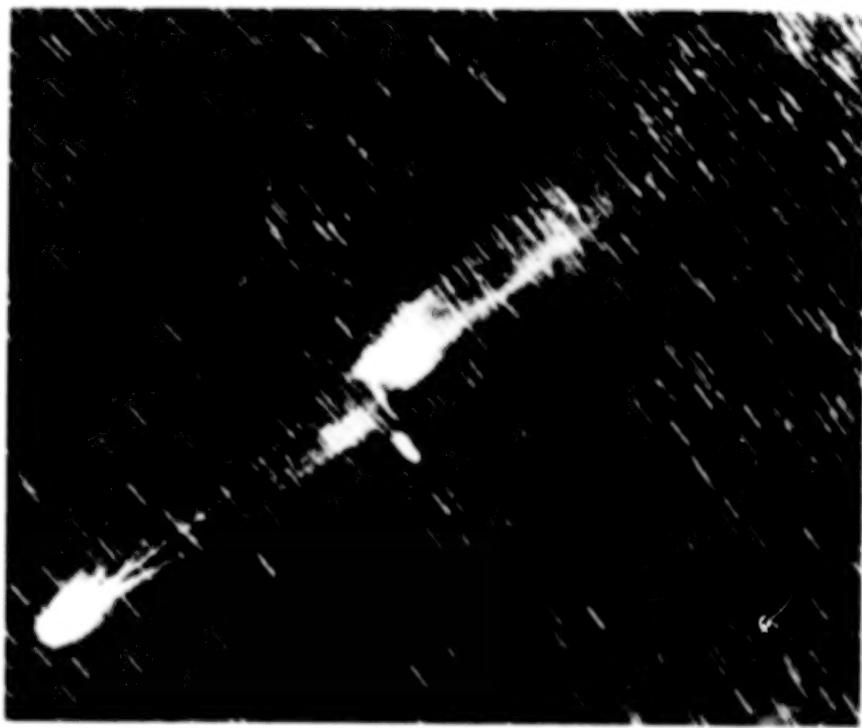
Fig. 13. Two photographs of Comet 1908 III Morehouse, showing a tail disconnection event. The upper photograph was taken on September 30, 1908, the lower one on October 1, 1908. Both photographs taken at Yerkes Observatory. (From Niedner and Brandt, 1978)

In order to summarize the possible science return from a mission to a comet, I reproduce in Table 3 a chart made up by our Chairman, Dr. Belton. This chart contains a listing of outstanding questions about comets that involve plasma physics studies, and it is clear that these questions must be answered if we are to understand comets. It is also worth summarizing the extent to which in situ comet studies will provide general understanding of space plasmas that have important implications beyond the study of solar system plasmas. In this context it seems clear that comet studies can provide fundamental information of general interest in the areas of magnetic field reconnection, the interaction of turbulence with magnetic fields, the behavior of large scale plasma flows, particle acceleration, charged particle transport, and collisionless shocks.

ACKNOWLEDGMENTS

Table 3.   Science Return from a Comet Rendezvous Mission

SCIENCE OBJECTIVE	SCIENCE RETURN
Characterize the interaction of a comet with the inter-planetary plasma and determine the origin and physical nature of comet tails.	The physical nature of tail phenomena observed from the ground. Insight into energetic geomagnetic and astrophysical phenomena. Whether there is a bow shock. Where it is. What its physical character is. Whether there is a contact surface. Where it is. What its physical character is. How ions are accelerated into the tail. Evidence on whether strong magnetic fields develop near the comet. The role wave motions and dissipation play in production of ionization and tail phenomena. Whether electric currents are induced in the atmosphere? An explanation of the "filaments" and "motions" seen in the plasma tail.

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COMETS: COSMIC CONNECTIONS WITH CARBONACEOUS METEORITES,

INTERSTELLAR MOLECULES AND THE ORIGIN OF LIFE

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ABSTRACT

In discussing the possible relationships of comets to carbonaceous meteorites and interstellar matter, emphasis is placed on aspects of their carbon chemistry. The suites of volatile and organic compounds associated with these bodies overlap. Thus, the ions, radicals, and molecules observed in comets may be derived intact or by partial decomposition from parent compounds of the sort found either in the interstellar medium or in carbonaceous meteorites. However, there appears to be a closer correlation between the molecular structures of cometary and interstellar molecules in that cyanides are common to both, but are absent in carbonaceous meteorites. These observations do not conflict with the view that comets and carbonaceous meteorites represent nebula condensates formed at different temperatures nor with the view that comets were assembled in the interstellar medium. Ambiguities surrounding the interpretation of measured ratios of ^{12}C to ^{13}C in cometary and interstellar molecules, coupled with the imprecision of the data, make them unsuitable for distinguishing between a solar system and interstellar origin for comets. If comets accreted in the solar nebula, there may be isotopic affinity between cometary carbon and the carbonate carbon of meteorites.

The early loss of highly reducing primitive atmosphere and its replacement by a secondary atmosphere dominated by H_2O, CO_2 and N_2, as depicted in current models of the Earth's evolution, pose a dilemma for the origin of life: the synthesis of organic compounds necessary for life from components of the secondary atmosphere appears to be difficult, and plausible mechanisms have not been evaluated. It is estimated that carbonaceous meteorites cannot have made a significant direct contribution of organic compounds to

the primitive Earth. Direct input of cometary organic compounds cannot be estimated for lack of data on the organic content of comets. Both comets and carbonaceous meteorites, however, are implicated as sources for the Earth's atmophilic and organogenic elements. A mass balance argument involving the estimated ratios of hydrogen to carbon in carbonaceous meteorites, comets, and the crust and upper mantle suggests that comets supplied the Earth with a large fraction of its volatiles. The probability that comets contributed significantly to the Earth's volatile inventory suggests a chemical evolutionary link between comets, prebiotic organic synthesis, and the origin of life.

I. INTRODUCTION

Scientific observations made during recent apparitions of the bright comets West, Bennett, and Kohoutek and the prospect of seeing Halley's comet in 1985-86 have aroused considerable enthusiasm among cometary scientists for intensified study of these objects. As a consequence, the possibility exists that a space mission to a comet may become a NASA objective in the 1980's. This article examines various aspects of organic cosmochemistry so as to stimulate and focus widespread interest in the nature and origin of comets and their possible relationships to interstellar molecules, meteorites, and the origin of life.

A fundamental premise of this article is that the study of comets or of any other primordial matter in the solar system really is a study of origins. Indeed, the study of comets comprises an integral aspect of what might be considered a cosmic quest for an understanding of our origins, starting from the "big bang" and leading eventually to interstellar dust, solar nebula, sun, planets, and the origin of life. In this context, a comet mission is one that most people can understand and support. In fulfilling this mission, we may learn more about our own origins in the cosmos and also discover more about the constraints that stellar and planetary evolution impose on the origin and distribution of extraterrestrial life. The latter knowledge then helps narrow future searches for intelligent life among the stars.

Just as biological evolution assumes that all organisms have a common ancestry, so chemical evolution assumes that all matter in the solar system had a common origin. Consider the following scenario: an interstellar cloud of dust and molecules collapses, perhaps triggered by a nearby supernova, thus beginning the chemical evolution of the nascent solar system. From the

solar nebula emerges the sun, planets, and other bodies of the solar system, including comets. The fall of meteoroids, meteorites, and cometary particles, large and small, contributes mass to the planets, as do particles injected by the solar wind. Sometime within 0.5 and 1.2 Gyr of the Earth's birth, life arises on its surface, and biological evolution begins. Eventually the death of the sun is perhaps accompanied by the ejection of matter back into the surrounding interstellar medium that originally spawned it. (This cycle in the condensation and dispersal of matter is depicted schematically in Fig. 1.)

According to this scenario, the origin and evolution of life on Earth was, and will continue to be, inextricably bound to the evolution of the sun and the Earth. Ironically, life evolved on a planet in which hydrogen, carbon, and nitrogen among the four major organogenic elements, hydrogen, carbon, nitrogen, and oxygen, are severely depleted with respect to the parent sun (Table I). Yet, there is satisfaction in knowing that the chemistry of life is based on four of the five most abundant elements in the cosmos (Table I). From this knowledge springs the conviction that organic chemistry constitutes an integral and fundamental aspect of cosmochemistry. Therein lies the anticipation that, despite the seeming improbability of its origin on Earth, life may be widely distributed in the cosmos.

In an evolutionary sense, human beings are the products of countless changes in the form and content of primitive matter wrought by processes of chemical and biological evolution. Biological evolution, as taught by Darwin, proceeds by accidental mutations; we are, therefore, the products of innumerable chance occurrences. Surely, in a cosmos whose order and harmony cannot be clearly discerned, cosmic events that we can only classify now as accidental or fortuitous must have occurred along the path of chemical evolution

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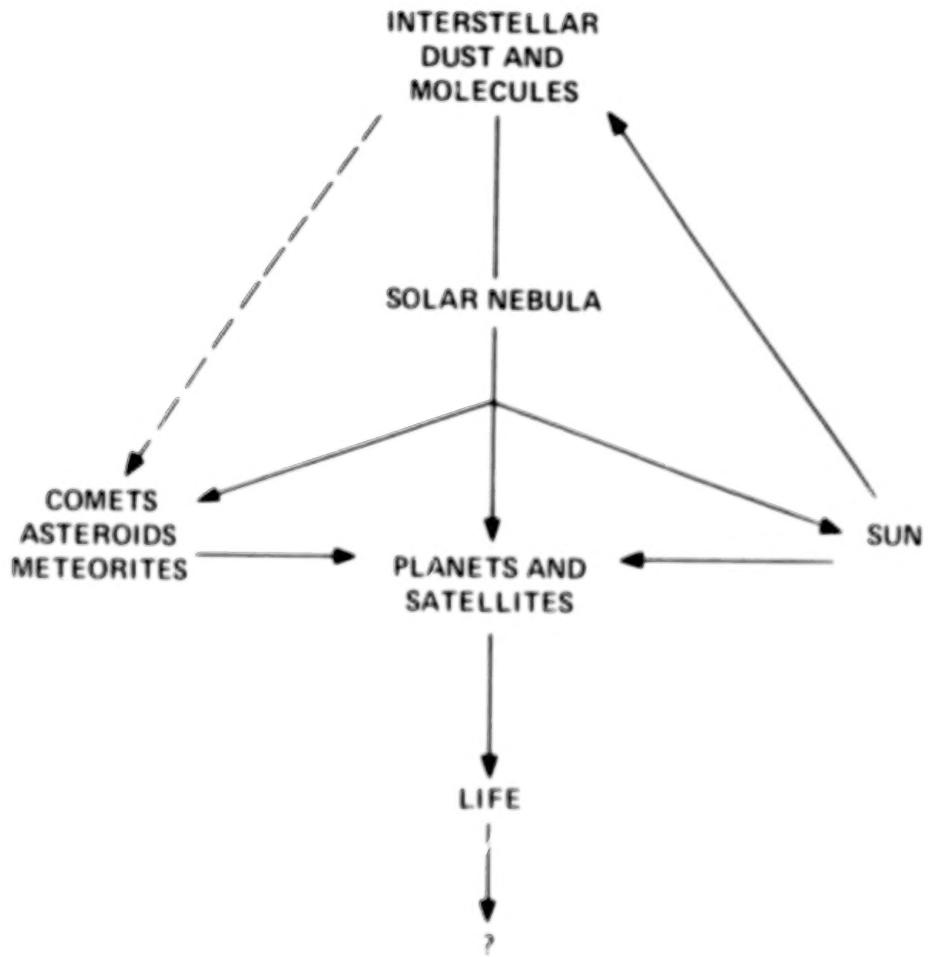
Fig. 1. Interrelationships between various bodies during chemical evolution of the solar system. Solid arrows indicate contributions of matter from one source to another. The dashed line signifies uncertainty regarding direct condensation of comets from interstellar matter. The arrow from "LIFE" implies its eventual dispersal from Earth.

TABLE I

RELATIVE ABUNDANCES OF SELECTED ELEMENTS

(In atom percent)

Element	Sun[a]	Earth[b]	Biosphere[*]
Hydrogen	94	0.95	64
Helium	6	~0	0
Carbon	0.04	0.01	9.1
Nitrogen	0.008	0.00002	0.1
Oxygen	0.07	49	27
Neon	0.004	~0	0
Sodium	0.0002	0.7	0.005
Magnesium	0.004	14	0.02
Aluminum	0.0003	4	0.0004
Silicon	0.004	14	0.03
Argon	0.0001	~0	0
Calcium	0.002	0.6	0.008
Iron	0.003	17	0.002

[a] Adapted from Ross and Aller (1976).

[b] Hydrogen, carbon, nitrogen data from Turekian and Clark (1975) for hydrosphere, atmosphere, crust, and upper mantle; other data adapted from Mason (1966) for total Earth.

[*] Mean percentages in terrestrial vegetation; adapted from Hutchinson (1968).

from interstellar matter to origin of life. How many of these events were essential to the origin of life? Is it possible, for example, that if the solar system had no comets, no life would have appeared? This last question is addressed in Section IV.

II. RELATIONSHIPS BETWEEN COMETS, SOLAR SYSTEM BODIES, AND THE INTERSTELLAR MEDIUM

At this point it is appropriate to indicate briefly the variety of cosmochemical issues that would be clarified by a better knowledge of comets. These issues focus on the relationships between comets, meteorites, and other bodies, both inside and outside the solar system. More detailed discussions of most of these issues, accompanied by leading references, can be found in Delsemme (1977). A widely held hypothesis states that the mineralogy and chemistry of carbonaceous meteorites reflect in part the equilibrium condensation of minerals from a cooling nebula gas of solar composition (Grossman and Larimer, 1974). Thus, carbonaceous meteorites are viewed as having accreted as mixtures in varying proportions of high- (>1,250 K) and low-temperature condensates and products resulting from subsequent alteration of these primary condensates in a relatively cool (<700 K) gas of solar composition and/or on the surface of a parent body. Wetherill (1976) argued persuasively that carbonaceous and chondritic meteorites are derived from Earth-approaching Apollo-Amor asteroidal bodies which, in turn, comprised the outgassed and compacted cores of moribund comets. Anders (1975) presented evidence of an alternative derivation of meteorites from main belt asteroids.

The birthplace of comets has been assigned a vast range of locations, from the asteroid belt to the distant interstellar medium. In a recent assessment of their place of origin, Delsemme (1977b) concluded that comets

originated in the outer regions of the solar nebula, in and beyond the space now traversed by the giant planets. Accordingly, comets, which have an apparently high endowment of volatile elements and compounds, may represent material accreted at low temperatures (Delsemme and Rud, 1977; Barshay and Lewis, 1976) at the distant edge of the solar nebula. Although an interstellar origin for comets has gained little support (see Delsemme, 1977b; Noerdlinger, 1977; and references therein), the recent discovery of similar molecular species in comets and in the interstellar medium suggests that contributions of interstellar matter to comets cannot be wholly discounted. If comets and interstellar clouds were genetically related, then spectroscopic observations of similarities in the chemistries of both would reflect commonalities in composition and origin. Meteorites may also be woven into this hypothetical relationship of comets and interstellar clouds. Recent analyses of trace mineral phases in carbonaceous meteorites reveal anomalous isotopic compositions for the elements oxygen, neon, magnesium, silicon, calcium, krypton, strontium, xenon, barium, neodymium, and samarium. (See Clayton, 1977; Frick, 1977; Lee et al., 1978; Lugmair et al., 1978; McCulloch and Wasserburg, 1978; Papanastassiou et al., 1978; Srinivasan and Anders, 1978; Yeh and Epstein, 1978; and references therein.) Inability to explain these anomalies with nuclear or nonnuclear processes within the solar system suggests that they are relics of presolar or interstellar matter which were incompletely homogenized in the solar nebula. If comets were samples of presolar matter preserved in bulk form, they would contain clues to the presolar history of this region of the galaxy.

The hypothesis that comets contributed substantial amounts of mass to some of the planets in the solar system appears widely accepted, particularly the idea that Neptune and Uranus were constructed from cometary building

blocks. Especially interesting is the possibility that comets supplied the terrestrial planets with a significant proportion of the volatile, atmophilic, organogenic elements (Whipple, 1976). Were this the case, comets may well have played a key role in the origin of life on Earth.

III. CARBONACEOUS METEORITES, COMETS, AND INTERSTELLAR MATTER

This section briefly describes carbonaceous meteorites and compares them with comets and interstellar matter, the emphasis being on organic chemical aspects. For more detailed information on meteorites and comets the reader is referred to Nagy (1975), Wasson (1974), and Delsemme (1977).

Carbonaceous meteorites consist of complex assemblages of relatively fine-grained mineral and organic matter that reflect a broad range of elemental compositions, textures, and petrologies, indicative of wide variations in the environment of origin for the various components. According to one prevailing model for their origins, some of the mineral ingredients were formed primarily by equilibrium condensation from the cooling gaseous solar nebula. Others resulted from alteration of the primary material. Presumably the diverse ingredients were eventually assembled into rocky material on parent bodies, possibly resembling asteroids, where compaction and the environmental conditions further influenced their chemistry, mineralogy, and petrology. Disruption of the parent bodies (perhaps by collison with other bodies) yielded fragments representative of the various parts which, in time, fell under the influence of the Earth's gravitational field. The identification of primary minerals and the elucidation of the possible secondary effects that can account for the observed compositions of meteorites constitute major efforts in meteorite research; the ultimate objective is to reconstruct the

physical and chemical environments and early histories of the solar nebula and the parent bodies.

Figure 2 summarizes major and minor phases found in carbonaceous meteorites, gives their probable temperature of formation by equilibrium condensation from the gaseous nebula or by secondary alteration, either in a solar composition gas or on a parent body, and shows their relative abundances and distributions in three types of carbonaceous meteorites. For present purposes, the major differences between the C3, C2, and C1 meteorites are their increasing content of volatile elements and decreasing content of minerals of high-temperature origin. Accordingly, the amount of organic matter increases in the same order from about 0.5 to 5% by weight. High-temperature inclusions containing melilite, spinel, and perovskite occur most abundantly in C3 meteorites, along with metal (iron and nickle) and the mafic silicates, olivine, pyroxene, which comprise the bulk of their mass. These minerals exist only in low to trace amounts in C2 meteorites; all, except for traces of mafic silicates, appear to be absent in the C1 meteorites.

A complex carbonaceous phase, characterized by insolubility in solvents and acids and a carbon-to-hydrogen ratio near 1, occurs as the major carbon component in all three types of meteorites, but is lowest in abundance in the C3 meteorites. Terrestrial sediments contain a material called "kerogen," which has similar characteristics but is of obviously different origin. To distinguish it from terrestrial kerogen, the meteoritic substance is designated as the acid-insoluble carbonaceous (AIC) phase. Figure 2 indicates its temperature of formation occurs at the midpoint of a ~500 K range. Although the production mechanism for this material in meteorites is unknown, carburization reactions used by the steel industry may provide relevant models; in
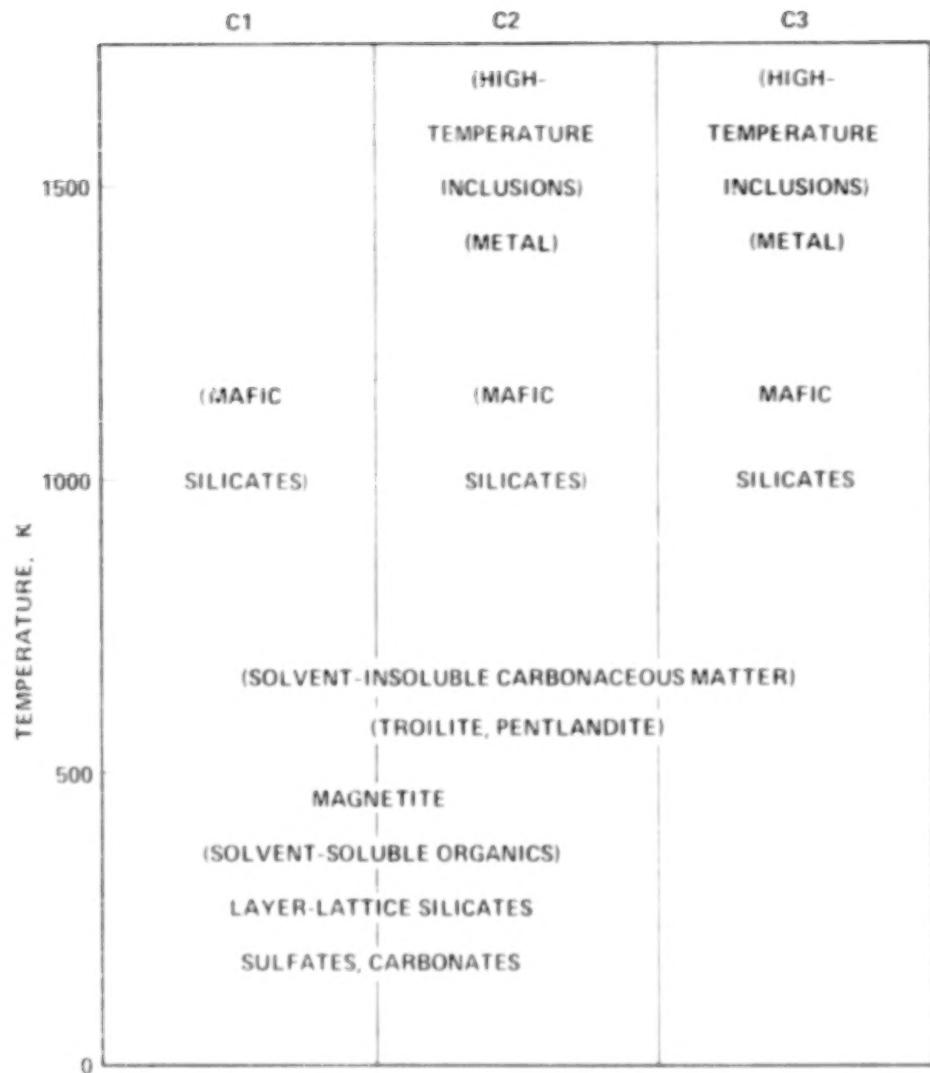
Fig. 2. Distributions and approximate condensation temperatures of minerals in carbonaceous meteorites (adapted from Wood, 1975). Parentheses indicate low to trace amounts.

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these reactions, the interaction of carbon monoxide with a metal surface heated to 500 to 1,100 K causes deposition of carbon within and on the surface (Freuhan, 1973; Meroc and Boulle, 1968). At lower temperatures, Fischer-Tropsch-type (FTT) reactions (Anders et al., 1973), also catalyzed by minerals, can produce the AIC substances. Organic synthesis promoted by FTT reactions, electric discharges, ultraviolet photochemistry, or other mechanisms must have occurred at temperatures sufficiently low to permit preservation of the variety of volatile and thermally labile organic compounds found in low abundances in C1 and C2 meteorites (see below). Although we are uncertain where these compounds were synthesized, many investigators favor production on a parent body rather than on mineral grains suspended in the solar nebula (Miller et al., 1976).

According to the equilibrium condensation model, the predominant sulfides (troilite, pyrrhotite, and pentlandite, which occur in minor amounts in all three types of meteorites) were formed at about 700 K by the reaction of hydrogen sulfide in the nebula gas with previously formed metallic iron and its alloys. Similarly, the model also hypothesizes that the magnetite found in C1 and C2 meteorites (5 to 15%) is produced by secondary reactions of metallic iron with water vapor at temperatures ≤ 400 K. Some of the magnetite, however, exhibits morphological and chemical characteristics suggestive of a primary condensation origin (Nagy, 1975). Magnetite occurs in trace quantities, if at all, in C3 meteorites.

The predominant minerals in C1 and C2 meteorites (50 to 80%) are the layer-lattice silicates or phyllosilicates. These minerals resemble terrestrial clays in crystallographic structure, but exhibit elemental compositions remarkably similar to the pattern of cosmic abundances. This

similarity suggests a primary origin for this material (Arrhenius and Alfvén, 1971; McSween and Richardson, 1977), but the likelihood of direct condensation as stable minerals from a solar composition gas has not been quantitatively assessed. A more likely mode of production involves hydrothermal alteration at about 350 K of previously formed silicates in an unknown environment (Bostrom and Fredriksson, 1966; Kerridge, 1977; Bunch and Chang, 1978; and references therein). Also found only in C1 and C2 meteorites are minor amounts of sulfates and carbonates. These too, apparently, have a predominantly secondary origin.

Although the effects of water on the mineralogy of C1 and C2 meteorites are evident, considerable uncertainty exists regarding the amount of free water that they contain. Apparently, the meteorites are easily contaminated with terrestrial water. Kaplan (1971) has critically reviewed the data and estimated upper limits of 10 and 5% for the total water content in C1 and C2 meteorites, including both free water and water bound as water of hydration in minerals, as phyllosilicate lattice hydroxyls, and as hydrogen in organic matter. Thus, a relatively small amount of water remains in these meteorites, despite its apparent major influence in the past.

The column sequence from right to left in Fig. 2 passes from C3 meteorites, which were apparently isolated from the physical and chemical effects of a low-temperature (<500 K) environment, to C2 and C1 meteorites, which contain only trace relics of high-temperature minerals and show abundant signs of exposure to a low-temperature environment containing gaseous and/or liquid water. To accommodate comets as the low-temperature end-member of a condensation sequence, one could construct a fourth column on the left of Fig. 2 in which the rock-forming minerals, sulfates, carbonates, and organic compounds

are minor constituents, and water and CO_2 ices constitute the major components (Delsemme, 1977a). Spectra of cometary meteoroids (Millman, 1977) and laboratory analyses of interplanetary dust (Brownlee et al., 1977) indicate that the nonvolatile component of comets bears strong resemblance to that of C1 and C2 meteorites. If the cometary matter condensed at ≤ 300 K, however, the mineralogy would likely bear little resemblance to that of carbonaceous meteorites. Indeed, if comets are formed at a great distance from the inner solar nebula, their mineralogy and chemistry are expected to resemble more closely those of interstellar grains.

Table II lists the atoms, ions, and molecules that have been detected in the interstellar medium, comets, and carbonaceous meteorites. These components are listed under the general class of organic compounds to which they belong or from which they can be produced by partial decomposition. Data for the table were taken from Delsemme (1975), Hayes (1967), Jungclaus et al., (1976, 1976a), Nagy (1975), Zuckerman (1977), and references therein. Repeated entries under the heading Comets (e.g., H, C, CO^+) reflect the variety of organic compounds that may serve as precursors. Within each compound class the organics of the meteorite are listed in order of decreasing abundances. Phyllosilicate and carbonate mineral species are also included because they occur in abundance and represent inorganic analogs of organic alcohols and acid derivatives, respectively. Spectroscopic and polarimetric observations and detection of SiO indicate that silicates also exist in the interstellar medium (Greenberg, 1973; Day, 1974). Although the cometary species can be derived from both interstellar and meteoritic compounds, the closer correlation between the molecular structures of cometary and interstellar species does not necessarily show a genetic relationship between the

TABLE II

ATOMS, IONS, AND MOLECULES DETECTED IN THE INTERSTELLAR

MEDIUM, COMETS, AND CARBONACEOUS METEORITES

Interstellar molecules	Comets	Carbonaceous meteorites
Hydrocarbons CH, CH^+, HC_2, HC_2H, HC_2CH_3	H, C, CH, CH^+, C_2, C_3	Aliphatics, Alicyclics, aromatics, C_1 to C_{20}
Alcohols OH, H_2O, CH_3OH, C_2H_5OH	H, O, OH, OH^+, H_2O, H_2O^+	Phyllosilicates, H_2O, C_1 to C_4 alcohols
Aldehydes and ketones HCO, HCO^+, H_2CO, CH_2CO CH_3CHO	H, C, CO^+	$C_2 - C_5$ aldehydes and ketones, H_2CO
Acids and derivatives CO, HCO_2H, HCO_2CH_3	H, C, O, CO^+, CO_2^+	$CO_3^=$, CO_2, C_2-C_8 mono and dicarboxylic acids, CO
Amines and derivatives NH_3, CH_2NH, CH_3NH_2, NH_2CHO, NH_2CN, $HNCO$	H, NH, NH^+, NH_2, N_2^+, CH, HCN, CO^+	Amino acids, C_1-C_4 amines, NH_3, N-heterocycles
Nitriles CN, HCN, HNC, NH_2CN, C_2CN, HC_2CN, H_2C_2HCN, CH_3CN, C_2H_5CN, HC_4CN	H, CN, HCN, CH_3CN	
Miscellaneous H_2, H_2CS, CS, SO, OCS, H_2S, SO_2, NS, SIO, N_2H^+, CH_3OCH_3	N_2^+	O- and S-heterocyclics

two, although it does accord with the view that comets were accreted from interstellar matter. Especially significant is the abundance of interstellar and cometary molecules (nitriles or cyanides) containing the CN fragment, and the apparent lack of similar molecules in meteorites. While the analyses of meteorites have not been directed at seeking nitriles, their presence would have been revealed in the course of many investigations (see below).

Using the known distribution of cometary ions, radicals, and molecules, we may be able to reconstruct the chemical composition of comets. The lack of a piece of comet for study makes this reconstruction essential to understanding what comets are. In the "dirty ice" model (Whipple, 1950; Whipple and Huebner, 1976), comets consist of simple and complex organic molecules and meteorite-like dust imbedded within a matrix of frozen H_2O and other gases. Near the sun, the volatile ice constituents evaporate, ejecting volatile compounds (e.g., H_2O, CH_4, CO_2, NH_3) and nonvolatile dust from the nucleus. According to this model, interaction of the parent compounds with solar photons and solar wind particles produces most of the observed cometary species by dissociation and ionization.

Recently, Oppenheimer (1975) questioned the necessity or relevance of some candidate parent molecules because their rates of photodissociation were too slow to account for the observed molecules. In his scheme, starting only with molecular hydrogen or a hydrogen-bearing molecule (such as methane plus atoms of other elements), gas phase ion-molecule reactions, similar to those postulated to account for formation of simple interstellar molecules, can produce the observed species in a comet's coma. The influence of ion-molecule reactions on the ionic species of comet tails has also been discussed by Wyckoff and Wehinger (1976). Ion-molecule reactions also appear able to

reshuffle rapidly the constituent atoms of parent molecules. The implication
is that the nucleus may have a composition different from the frozen ice
model. Clearly, under these circumstances, reconstruction of the physical
and chemical state of the nucleus from the identity, abundance, and distribu-
tion of observable species poses a formidable task having more complications
than originally thought. However, since ion-molecule reactions have not yet
been shown to provide promising pathways for formation of the observed CH_3CN
(Heubner, 1977), the concept of the parent molecule still retains its rele-
vance to the chemistry of comets. Moreover, interpretations of ultraviolet
observations of comets by Keller (1976) show how the production of H and OH
can be correlated with the presence of H_2O as a major parent molecule.

Examination in more detail of the organic compounds in carbonaceous
meteorites may provide additional insight into the organic chemical composi-
tion of comets. Table III shows the distribution of carbon in the Murchison
meteorite, the most pristine and carefully examined carbonaceous meteorite.
Note that the volatile organic compounds, the hydrocarbons, carboxylic acids,
ketones, aldehydes, alcohols, and amines, constitute a small fraction of the
total carbon and less than 0.05% of the total mass of the meteorite. The
amino acids that have drawn so much attention occur in minute amounts. Since
the sum of the listed compounds agrees well with the total amount of carbon,
we are confident that no major reservoirs of carbon have been overlooked.
While carbonate minerals exist in the Murchison meteorite, their abundance is
based on the amount of CO_2 released by acids. Therefore, it is not clear
whether or not some fraction of that gas was actually CO_2 trapped in the
meteorite matrix.

TABLE III

DISTRIBUTION OF CARBON IN MURCHISON METEORITE[2]

Acid insoluble carbona- ceous phase, %	1.3 to 1.8
CO_3^-, %	0.2 to 0.5
Hydrocarbons and lipids, %	0.07 to 0.11
Carboxylic acids, ppm	~350
Amino acids, ppm	10 to 30
Ketones and aldehydes, ppm	~17
Urea and amides, ppm	<2 to 15
Alcohol, ppm	~6
Amines, ppm	~2 to 3
N-heterocycles, ppm	~2 to 40
Sum: 1.81 to 2.45%	
Total carbon: 2.0 to 2.58%	

[2]Estimates are based on data provided by Kvenvolden
et al. (1970), Folsome et al. (1971), Cronin and
Moore (1971), Yuen and Kvenvolden (1973), Lawless et al.
(1974), Pereira et al. (1975), Hayatsu et al. (1975),
Jungclaus et al. (1976, 1976a), Chang et al. (1978),
Van Der Velden and Schwartz (1977), Jada and Peltzer (1978).

Table IV shows the volatilization characteristics of carbonaceous meteoritic material. The data correspond to abundances of the indicated ions (relative to CH_4 at 423 K) obtained from mass spectra of the gases volatilized under vacuum over the temperature range 325 to 1,500 K. The sample is a C2 inclusion removed from Jodzie, a howardite meteorite (Bunch et al., 1976). However, the C2 meteorites, Murchison and Murray, give essentially similar results (Simoneit et al., 1973; Wszolek et al., 1973). Below 423 K, adsorbed terrestrial H_2O is mostly evolved; at 423 K, molecules of H_2O, CO_2, and CH_4 are released. The H_2O is derived predominantly from dehydration of phyllosilicate minerals; the CO_2 probably results from decomposition of carbonates and organic matter and release of trapped gas; the CO appears to be produced in the mass spectrometer as a fragmentation product of the CO_2^+ ion. Neither HCN nor CH_3CN evolved in significant amounts at 423 K. At 673 K, traces of HCN are released as a thermal decomposition product of other substances, as are all the other indicated species. Volatilization of meteoritic compounds into a mass spectrometer in which the compounds are ionized and fragmented into primary and secondary ions is a process analogous to a putative cometary process. Comparison of data in Table IV with the production rates in Table V shows that the major meteoritic volatiles, and fragments derived from them, can account qualitatively for the predominant cometary species; but the parent molecules involved and the temperatures required may differ greatly. Nonetheless, this agreement does not conflict with the view that comets and carbonaceous meteorites represent nebula condensates formed at different temperatures or with the view that comets were assembled in the interstellar medium. Obviously, the suite of volatile and organic components in comets and C2 (and C1) meteorites may overlap somewhat. The absence of HCN

TABLE IV

RELATIVE ABUNDANCES OF IONS CORRESPONDING TO
VOLATILES RELEASED BY VACUUM PYROLYSIS FROM
CM2 CHONDRITES AT 423 AND 673 K

Ion species	423 K	673 K
H_2O	36	60
CO_2	5.0	200
CO	2.0	10
CH_4	1.0	4.0
N_2	0.2	0.2
SO_2	0.04	0.8
C_3H_6	0.03	0.4
C_2H_4O	0.02	0.2
HCN	<0.01	0.1

TABLE V

PRODUCTION RATES OF COMETARY SPECIES

(In 10^{28} sec $^{-1}$, reduced to R = 1 AU; adapted from Delsemme, 1977a)

Species	1970 II Bennett	1973 VII Kohoutek	1976 VI West
H	54 to 65	34	46
OH	30	20	20
O	18	3.8 to 8.3	23
C		0.6 to 1.6	9.0
CO			8.5
C_2		0.1 to 0.04[a]	
CN		0.04 to 0.01[a]	
HCN		0.01 to 0.1	
CH_3CN		0.01 to 0.1	

[a]Production rate before perihelion to after perihelion.

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and CH_3CN in meteorites, coupled with a relatively low water content when compared to comets, points to differences in volatiles content and organic chemistry that relates to differences that prevailed in the respective environments of formation. Note that the organic compounds observed in meteorites, comets, and the interstellar medium represent the products of kinetic rather than equilibrium thermodynamic processes (Barshay and Lewis, 1976). Elucidation of their formation will provide both insight into the dynamics of the environments in which they formed and constraints on models that purport to describe these environments.

What evidence can be brought to bear on the question of where comets were formed? One approach compares the isotope ratios of ^{12}C to ^{13}C for cometary carbon with carbon in the solar system, in other stars, and in the interstellar medium. Since the isotopic ratios of elements reflect the nucleosynthetic pathways of formation, we may be able to tell whether comets originated in the solar system or in the interstellar medium.

As expected, the data in Table VI show a common value of about 90 for the ratios of ^{12}C to ^{13}C in solar system bodies. Comets exhibit both higher and lower ratios; but the differences appear insignificant in light of uncertainties in the measurements. Red giant stars cover a fairly narrow range from 12 to 51. Carbon stars and the interstellar medium exhibit rather wider ranges of isotopic composition. Vanysek (1977), however, argues that the reliable interstellar values center around 40; he concludes that the difference between this value and the factor-of-two larger ratios for comets precludes an interstellar origin for comets. While this appears a reasonable conclusion, laboratory studies and model calculations of ion-molecule reactions involving C^+ and CO indicate that kinetic isotope effects can yield

TABLE VI

RATIOS OF ^{12}C TO ^{13}C IN THE COSMOS

Object	Diagnostic Species	$^{12}C/^{13}C$	LITERATURE
Sol	CO	90 ± 14	a
Venus	CO_2	~100	b
Earth	Various	89 (+7, -1)	c
Moon	Various	89 ± 2	d
Mars	CO_2	87 ± 2	e
Meteorites	Various	89 (+3, -6)	d
Jupiter	CH_4	89 (+12, -10)	f
Saturn	CH_4	89 (+25, -18)	f
Interstellar medium	CH^+, CO, H_2CO	>13 to 105	g
Red giant stars	CN	12 to 51	h
Carbon stars	C_2, CN	2 to ≥100	i
Comets:			
Ikeya (1963 I)	C_2	70 ± 15	j
Tago-Sato-Kosaka (1969 IX)	C_2	100 ± 20	j
Bennett (1970 II)	C_2	≥50	j
Kohoutek (1973 VII)	C_2	115 (+30, -20)	j
		135 (+65, -45)	j
Kobayashi-Berger-Milon (1975 IX)	C_2	110 (+20, -30)	j

[a] Hall et al. (1972)

[b] Connes et al. (1968).

[c] Wedepohl (1969).

[d] Kaplan (1975).

[e] Nier et al. (1976)

[f] Combes et al. (1977).

[g] Bertojo et al. (1974); Matsakis et al. (1976), and references therein.

[h] Lambert and Sneden (1977) and references therein.

[i] Scalo (1977) and references therein.

[j] Vanysek (1977) and references therein.

CONTENTS

rather large isotopic fractionations, which may obscure the true ratio of ^{12}C to ^{13}C in the interstellar medium (Watson et al., 1976; Langer, 1977). Since the same ion-molecule reactions may play important roles in comet chemistry, the observed isotope ratios of comets may be similarly influenced. These ambiguities surrounding the interpretation of carbon isotope ratio measurements make them unsuitable at this time for clearly distinguishing between a solar system or interstellar origin for comets.

If it is assumed that comets, like meteorites, did form in the solar system, a more detailed look at the carbon isotope ratios in meteorites may be instructive. Figure 3 plots the isotopic composition of carbon versus total carbon content of meteorites. The precision of these laboratory analyses permits distinction of part per thousand variations in the isotope ratios, whereas the astronomical measurements of Table V allow precision of only tens of percent. Increasingly negative values for $\delta^{13}C_{PDB}$ signify increasingly higher ratios of ^{12}C to ^{13}C relative to a standard. The C1 and C2 meteorites occupy a part of the field in the figure that is quite distinct from the C3 and other meteorites. While the reasons for the isotopic variations between types of meteorites are not understood, the data indicate a high degree of carbon isotopic heterogeneity in the early solar system (see also Kung and Clayton, 1978). When the isotopic composition of various carbonaceous phases is displayed as in Fig. 4, the extensive isotopic heterogeneity within single meteorites becomes apparent. This heterogeneity cannot be readily explained simply as resulting from kinetic isotopic fractionation associated with the synthesis of the various phases in Fischer-Tropsch-type reactions, as postulated by Lancet and Anders (1970). The various forms of meteoritic carbon, which have various ranges of isotopic composition, may represent at least two

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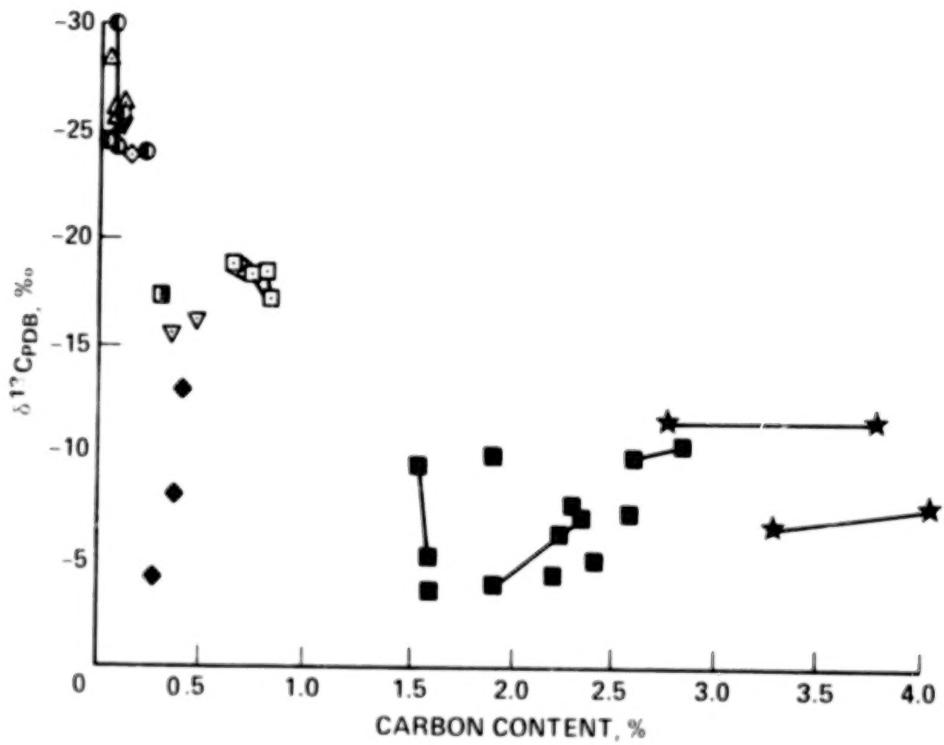
Fig. 3. Plot of carbon isotope ratio versus total carbon abundance for various meteorites. The lines connect independent analyses of the same meteorite. ★ = C1; ■ = C2; □, ◨, ▽ = C3; ▼ = C4; △, ◐ ordinary chondrites; ◆ = enstatite chondrites (see Wasson, 1974, for descriptions of the various types of meteorites not discussed here). The isotopic compositions are given as δ-values relative to the Peedee belemnite limestone standard and are defined in the following fashion:

$$\delta^{13}C_{PDB} = [(R_{Sample}/R_{Standard}) - 1] \times 10^3, \quad R = {}^{13}C/{}^{12}C.$$

Data are taken from Boato (1954), Belsky and Kaplan (1970), Smith and Kaplan (1970), Kvenvolden et al. (1970), and Chang et al. (1978).
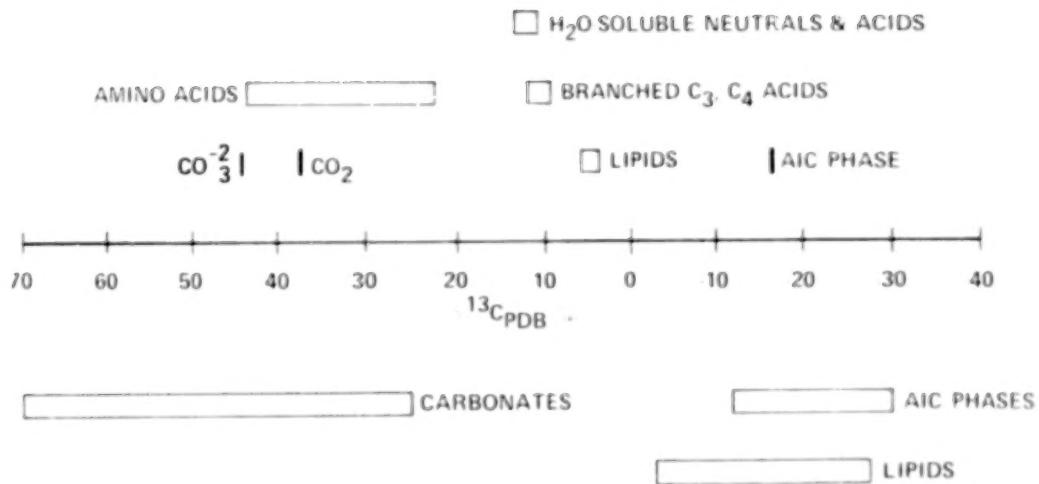
Fig. 4. Isotopic composition of carbon phases in Murchison (above the scale line) and in other carbonaceous meteorites. AIC phase corresponds to acid insoluble carbonaceous phase. Data are taken from references given in the caption of Fig. 3. The data from lipids in Murchison are judged to be least influenced by exposure to terrestrial contamination.

stages of carbon condensation in the early nebula, each of which occurred in a different environment separated in space and in time. Presumably, accretion of the meteorite parent bodies brought together carbonaceous as well as other mineral phases from isotopically different regions of the solar nebula. In particular, the large isotopic separation between the relatively reduced acid-insoluble carbonaceous phase and the oxidized carbonate and amino acid phases may reflect different origins. This view agrees with the concept that an incompletely homogenized solar nebula seems required to rationalize the isotopic anomalies associated with other elements (see Section II).

C3 meteorites exhibit a high-temperature history and a relatively reduced state; acid-insoluble carbonaceous matter relatively enriched in ^{12}C (negative $\delta^{13}C$ value) comprises the only significant carbon phase. C2 meteorites reflect extensive exposure to a low-temperature environment; they contain both the acid-insoluble carbonaceous matter and the oxidized carbon phases relatively enriched in ^{13}C (positive $\delta^{13}C$ values). C1 meteorites are the most highly oxidized, and they contain the most carbonate with the highest ^{13}C abundances. For these meteorites, an isotopic trend is suggested that correlates ^{13}C enrichment with high carbon oxidation state and low-temperature environments. If the trend is real, then the low-temperature origin of comets and the relatively oxidized state required by postulated high abundances of H_2O and CO_2 would point to levels of ^{13}C enrichment in cometary carbon that exceed that of C2 and C1 meteorites. It is interesting to speculate that the ^{13}C-enriched phases in carbonaceous meteorites may have a cometary origin. This possibility could result if the low-temperature environment of the parent body acquired the C- and H-bearing species through the infall of comets (cf. next section). While the majority of the carbon

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isotopic measurements (Table V) hint that cometary ^{13}C abundances may be lower than those of Cl and C2 meteorites, the measurements are too imprecise to be meaningful.

While a number of aspects of the chemistry of comets, meteorites, and interstellar matter have been examined in this section, we are no more certain about the nature and origin of comets than when we started. Clearly, this stage of affairs emphasizes the need for a quantum jump in knowledge.

IV. COMETS, CARBONACEOUS METEORITES, AND THE ORIGIN OF LIFE

According to the Oparin-Haldane-Miller-Urey paradigm, a highly reducing atmosphere consisting of methane, ammonia, and water prevailed on the primitive Earth. Passage of energy in various forms through this hypothetical atmosphere produced the reservoir of organic molecules from which life evolved. The existence of this atmosphere required the presence of metallic iron in the upper mantle (Holland, 1962), which Walker (1976) pointed out appears incompatible with geochemical observations. Walker (1976) proceeded to develop a case in favor of a primitive atmosphere composed predominantly of CO_2 and N_2. His arguments derive from implications of the inhomogeneous accretion model of the Earth's origin as formulated and developed by Turekian and Clark (1969) and others (Walker, 1976). The relationships between meteorites and comets and the origin of life will be viewed in the context of this model.

The basic features of the model are depicted schematically in Fig. 5 and briefly summarized below. (The reader is referred to Walker (1976) and other references therein for a more detailed description.) In this model, refractory minerals condensing early from the cooling nebula accreted to form the protoplanet. Rapid accretion was accompanied by melting and segregation into molten metallic core and fluid silicate mantle. The initial inventory of
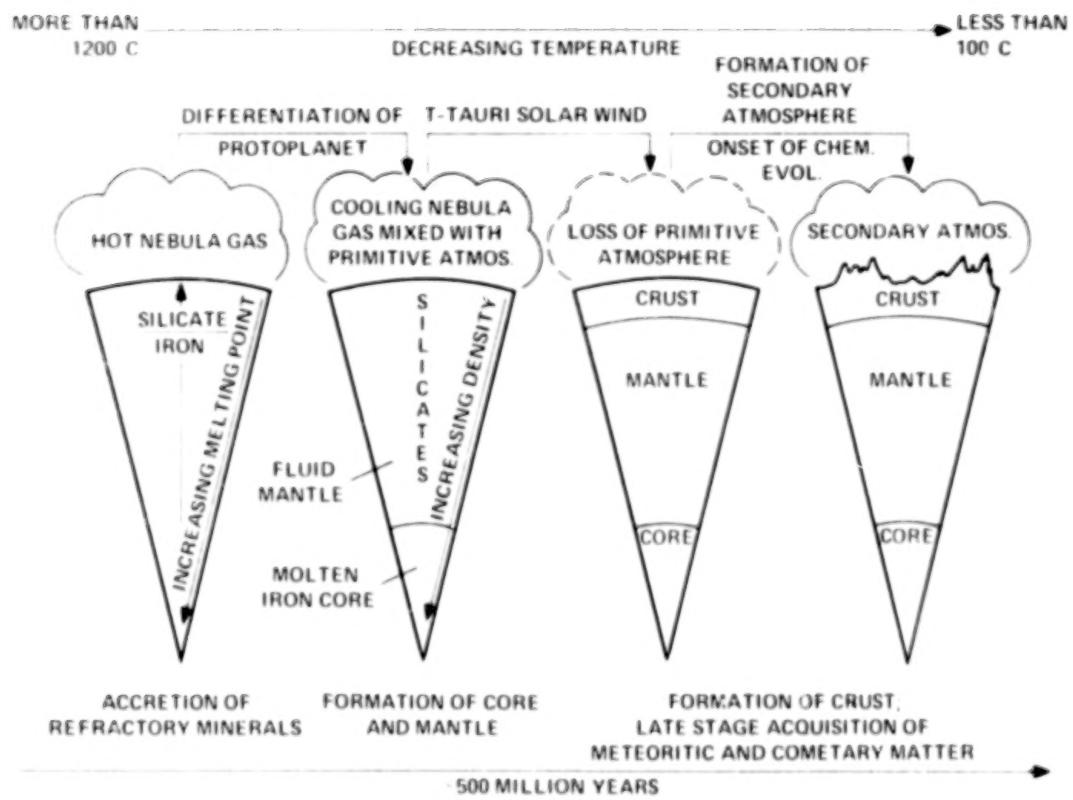
Fig. 5. Stages in the Earth's early evolution.

volatiles was driven to the surface. As the nebula gas continued to cool, metallic iron was converted to the ferrous state. Presumably, when the sun passed through its T-Tauri stage, the powerful solar wind blew the remaining nebular gas out of the inner solar system, carrying the Earth's primitive atmosphere with it. Because doubt exists about the efficacy of the T-Tauri wind, it is significant that another mechanism has been identified that could have achieved the same result. In his recent discussion of a physical model of the primitive solar nebula, Cameron (1978) suggested that tidal stripping of the atmospheric envelope of a giant, gaseous, inner protoplanet by the sun could have occurred early, leaving behind a core of condensed matter. Debris from the nebula condensation was accumulated by the primitive Earth. This debris provided both refractory and volatile-rich material to form the thin crustal veneer of the Earth. Heating of this late-accreted debris either during passage through the atmosphere, during impact with the surface, or while imbedded in a hot surface, released the volatiles to form the secondary atmosphere. As a result of the Earth's continued cooling, a thin, solid, but still hot, crust probably existed about 4.1 to 4.0 Gyr ago. The crust must have formed by about 3.9 Gyr because shortly thereafter aqueous environments and sedimentary processes had begun, as evidenced by the 3.8-Gyr-old metasedimentary rocks of Greenland. (See Allaart, 1976, and references therein.) About 3.3 Gyr ago, life was already depositing evidence of its existence in sediments now located in South Africa (Eichmann and Schidlowski, 1975; Schopf, 1975). The span between about 4.0 and 3.3 Gyr ago, therefore, represents the time within which chemical evolution proceeded to the origin of life.

An important outcome of the study of lunar rocks was the discovery that a late period of intense bombardment of the lunar surface ended about 3.9 Gyr ago (Tera et al., 1974). This finding supported the idea that the initial geomorphology of the crustal veneer and the composition of secondary atmospheres

of all the terrestrial planets were produced by late-stage impacts. Computer modeling of the late-stage accretion by Benlow and Meadows (1977) yielded an amount of volatiles derived from vaporization of Cl meteorites that was of the same order of magnitude as the present terrestrial inventory. Dynamic considerations indicate that both comets and meteorites could have been the impacting bodies (Wetherill, 1975, 1976, 1977; Whipple, 1976).

According to Walker (1976), H_2O and CO_2 dominated the secondary atmosphere; N_2 occurred in minor amounts; and H_2 and CO were present only in traces, if at all (cf. Table IV). Traces of CH_4 and other hydrocarbons were presumed to have been oxidized readily in CO_2 by iron oxides. The composition of this steam atmosphere was determined by the redox potential of the silicate crust and upper mantle and would have strongly resembled contemporary volcanic exhalations. The subsequent evolution of Walker's secondary atmosphere is depicted in stepwise fashion in Fig. 6. Once the temperature of the Earth dropped below 373 K, water condensed to begin formation of the oceans and weathering of basic igneous rocks by CO_2 afforded carbonates. The prebiotic atmosphere that resulted closely resembled the present atmosphere minus oxygen.

Although production of the organic compounds necessary for chemical evolution would have proceeded readily in a highly reducing atmosphere, the possibilities in a CO_2-N_2-H_2O atmosphere with traces of H_2, CO, and/or CH_4 remain essentially unexplored. Of the various energy sources on the Earth today (Table VII), ultraviolet light (1500 Å) and electric discharges are the only significant ones available on a global scale; there appears to be no compelling reason to assume a different situation for the primitive Earth. The difficulties in synthesizing key compounds such as amino acids in a

STEAM ATMOSPHERE: 300 atm H_2O
                             50 atm CO_2
RAPID H_2O 0.8 atm N_2 C
CONDENSATION   TRACES (?)   H
                               H_2, CO, CH_4 E
                                                     M
CO$_2$ RICH ATMOSPHERE: 50 atm CO_2 I
                             0.8 atm N_2 C
CO$_2$ WEATHERING   TRACES (?)   A
AND CARBONATE H_2, CO, CH_4 L
FORMATION
                                                     E
                                                     V
                                                     O
PREBIOTIC ATMOSPHERE: 0.001 atm CO_2 L
                             0.8 atm N_2 U
                             TRACES (?)   T
                               H_2, CO, CH_4 I
                                                     O
                                                     N

                                          ORIGIN OF LIFE

PRESENT ATMOSPHERE: 0.0003 atm CO_2
                             0.2 atm O_2
                             TRACES H_2,
                               CO, CH_4
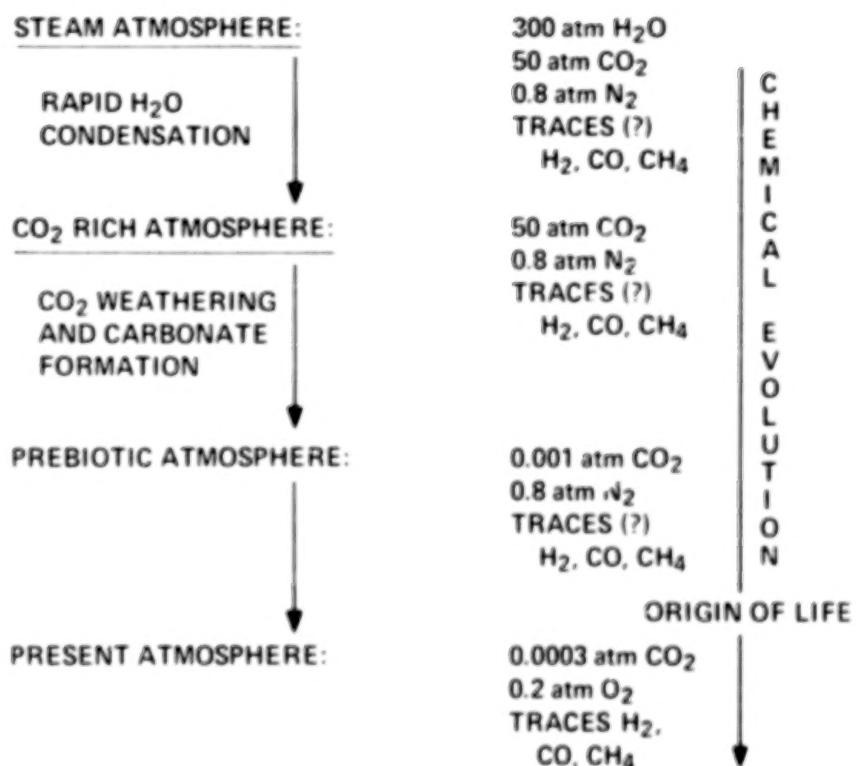
Fig. 6. Stages in the evolution of the secondary
         atmosphere.

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TABLE VII

ENERGY SOURCES ON THE CONTEMPORARY EARTH

(Adapted from Miller and Urey, 1959)

Source	Energy, cal/cm^2 yr
Total solar radiation	260,000
Ultraviolet light	
Less than 2500 Å	570
Less than 2000 Å	85
Less than 1500 Å	3.5
Electrical discharges	4.0
Radioactivity (to 1 km depth)	0.8
Volcanoes	0.13
Cosmic rays	0.0015

CO_2-N_2-H_2O atmosphere have been pointed out by Gabel (1977). Even with CH_4 replacing CO_2, Ferris and Chen (1975) were unable to produce amino acids by ultraviolet photochemistry. In our own laboratory, electric discharges through CO_2-N_2-H_2O mixtures afforded nitric acid as the major product rather than organic compounds. Clearly, the presence of a reducing gas (H_2, CH_4, or CO) is required if organic synthesis occurred in the atmosphere. Walker (1976) offered the possibility that H_2 produced volcanically through decomposition of H_2O in early tectonic processes and amounting to about 1% of the atmosphere could have persisted for about 0.5 Gyr on the early Earth. Whether or not this amount would have been sufficient to permit organic synthesis remains to be evaluated. If not, how were the basic chemical building blocks of life made available? Hartman (1975) and Gabel (1977) offer some schemes that require re-actions in the oceans and on clays, but none has been assessed in a critical or quantitative experimental fashion. Especially noteworthy, however, are Baur's (1978) thermodynamic calculations which indicate that spontaneous formation of reduced organic matter, including amino acids, can occur in heterogeneous systems containing N_2 and CO_2 in the presence of Fe(II)-containing minerals and H_2O. Investigations of the potential pathways for organic synthesis in such hetero-geneous systems are highly desirable.

Let us consider the possibility that organic compounds were directly supplied by the leaching and weathering of carbonaceous meteorites that reached the surface of the Earth intact without significant heating. A simple model-dependent calculation can set upper limits on the amounts of amino acids supplied by this mechanism. Evidence from lunar studies points to termination of the late accretion stage at about 3.9 Gyr. Data of Wetherill (1977) indicate that the impact rate probably decreased exponen-tially over the period 4.5 to 3.9 Gyr ago from values of about 50×10^4 to 10^4

times the present infall rate of 10^3 g s^{-1} (Dohnanyi, 1971). We can assume that a solid crust sufficiently thick to support impacting bodies existed by 4.1 Gyr ago. High surface temperatures, which would lead to amino acid destruction, probably prevailed prior to this point in time. These considerations provide the basis for estimating that the mass of material delivered between 4.1 and 3.9 Gyr ago would amount to about 10^{23} g. If (a) 50% of the mass had C1 or C2 meteorite composition, (b) 10% of it arrived at the Earth's surface intact, (c) the early oceans were as large as they are today (1.3×10^{21} %), and (d) the 30 ppm C abundance as amino acids (see Table III) was all leached out by weathering and transferred to the oceans without loss, then the amino acids would form a highly dilute 5×10^{-7} molar solution. Assumptions (a), (b), and (d) are greatly optimistic (each by factors of 10 or more) in light of contemporary experience; they should more than balance the assumption of present day ocean volume. Given this dilute solution, it is difficult to formulate a geologically reasonable scenario to concentrate the amino acids and continue the course of chemical evolution to more complex molecules. Either a richer source of organic matter was also involved or some undiscovered synthesis and accumulation mechanisms operated on the primitive Earth, or both. If, on the other hand, we assume for carbonaceous meteorites a maximum of 10% H_2O (Kaplan, 1971) and 30 ppm amino acid concentration (with average molecular weight of 100), simultaneous release of all H_2O and amino acids would yield a 0.003 molar solution. To release the hydrogen as H_2O, however, would require heating to temperatures in excess of 100°C, which would destroy the amino acids.

If the secondary atmosphere also contained a cometary contribution, comets could have supplied part or all of the initial inventory of organic

matter for chemical evolution, a suggestion first made by Oró (1961). Since we have no clear knowledge of the content of organic compounds or of all the percursors such as HCN in comets, we cannot make an estimate as we did for carbonaceous meteorites. Comparison of the scanty data on production rates in Table V and estimates of the dust-to-gas mass ratio in comets (<2; Delsemme, 1977a) with the abundances of organic compounds in meteorites (Table III) leads one to expect considerably higher abundances of volatile and extractable organic compounds in comets.

Even if comets did not directly supply organic matter, they may well have provided the early atmosphere with the reduced gases CH_4 and CO or HCN and other intermediates that seem to be required for organic synthesis. After H_2O and CO_2, CH_4 and CO may be the most abundant molecules in comets (Delsemme and Rud, 1977). Evaporation of these and other volatiles from an icy matrix rapidly and directly into the atmosphere during entry and impact would free them for atmospheric chemical transformations and lengthen their lifetime against conversion to CO_2 by minimizing contact with a hot silicate impact melt. In contrast, as was shown in Table IV, the volatiles in meteorites require relatively high temperatures to release them from the meteorite matrix; thus, the compounds obtained from meteorites must have been released largely by pyrolytic-oxidative reactions of precursive organic matter with the matrix and/or slow inefficient extraction by rain or other water reservoirs.

Although ignorance about compositions precludes a meaningful estimate of cometary organic compounds and reducing gases, it seems highly desirable to try to estimate how much of the Earth's volatile inventory may have been supplied by comets. The approach we take considers the hydrogen/carbon, nitrogen/carbon, sulfur/carbon and argon/carbon ratios in comets, meteorites,

and the Earth. Since all of these ratios are associated with rather large uncertainties, the quantitative significance of the estimate should be viewed with caution. The qualitative implications, however, should be seriously considered. Data needed for this estimate are given in Table VIII. Estimates of the ratios for the Earth's crust originate from three different sources and these supply limits for consideration. Note that Walker's model for the secondary atmosphere (Fig. 6) calls for hydrogen/carbon and nitrogen/carbon ratios of 12 and 0.03, respectively, comparable to the lowest values in Table VIII. The lack of correlation in hydrogen/carbon, sulfur/carbon, and [36]argon/carbon ratios between Earth and carbonaceous meteorites is striking. Relative to carbon, the Earth's crust contains more hydrogen and rare gases, and less sulfur than does any class of carbonaceous meteorite. Similar conclusions have been reported by Bogard and Gibson (1978). Some other source of volatiles must have contributed to the crust, and comets would appear to be reasonable alternatives (see also Bogard and Gibson, 1978; and Sill and Wilkening, 1978). Anders and Owens (1977), however, attribute the volatiles to a mixture of ordinary and carbonaceous meteorites dominated by the latter.

Table V supplies the appropriate data for comets. Upper and lower limits for the hydrogen/carbon ratio can be set at 90 and 4, respectively. Two mass balance equations for carbon and hydrogen are given below with the subscripts E, c, and M signifying the Earth's crustal content, the comet contribution and the meteorite contribution, respectively. Next, each term

$$C_E = C_c + C_M \tag{1}$$

$$H_E = H_c + H_M \tag{2}$$

in Eqs. (1) and (2) is divided by the quantity $(H + C)_E$. In the resulting

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TABLE VIII

ESTIMATES OF THE ATOMIC ABUNDANCES (RELATIVE TO CARBON)

OF VOLATILE ELEMENTS IN THE EARTH'S ATMOSPHERE, OCEANS,

AND CRUST AND IN CARBONACEOUS METEORITES

	Hydrogen/ carbon	Nitrogen/ carbon	Sulfur/ carbon	^{36}Argon/carbon $(\times 10^{-6})$
Earth[a]	87	0.14	0.03	–
Earth[b]	24	0.08	–	0.76
Earth[c]	16	0.03	0.07	0.49
C1 meteorites[d]	<4.2[e]	0.05[f]	0.64	0.013
C2 meteorites[d]	<3.1[e]	0.04[f]	0.63	0.014
C3 meteorites[d]	<2.5[e]	0.007[f]	1.5[g]	0.10[h]

[a]Rubey (1951).

[b]Turekian and Clark (1975).

[c]Anders and Owen (1977).

[d]Ratios are calculated as averages from data of Van Schmus and Hayes (1974), unless otherwise indicated.

[e]Calculated from upper limits for hydrogen, estimated by Kaplan (1971) and median carbon values of Vdovykin and Moore (1971).

[f]Calculated from averaged nitrogen data of Injerd and Kaplan (1974), Kothari and Goel (1974), and Kung and Clayton (1978) and median carbon values of Vdovykin and Moore (1971).

[g]Average value from a range of 0.34 to 2.86 for 16 meteorites.

[h]Average value from a wide range of 0.002 to 0.225 for 16 meteorites.

equations, the comet and meteorite components, respectively, are multiplied by the ratios $(H + C)_c/(H + C)_c$ and $(H + C)_M/(H + C)_M$. Rearrangement of the terms gives Eqs. (3) and (4)

$$C_E/(H + C)_E = C_c/(H + C)_c \cdot (H + C)_c/(H + C)_E + C_M/(H + C)_M \cdot (H + C)_M/(H + C)_E \quad (3)$$

$$H_E/(H + C)_E = H_c/(H + C)_c \cdot (H + C)_c/(H + C)_E + H_M/(H + C)_M \cdot (H + C)_M/(H + C)_E \quad (4)$$

Next, allow $X = (H + C)_c/(H + C)_E$ to represent the fraction of the Earth's total hydrogen and carbon that was contributed by comets. Thus $(1 - X) = (H + C)_M/(H + C)_E$ corresponds to the fraction supplied by meteorites. Division of Eq. (4) by (3) produces Eq. (5), which can be solved with the estimated hydrogen/carbon ratios. To calculate the

$$(H/C)_E = \frac{X[H/(H + C)]_c + (1 - X)[H/(H + C)]_M}{X[C/(H + C)]_c + (1 - X)[C/(H + C)]_M} \quad (5)$$

smallest value for X, we use the representative $(H/C)_M$ value of 3.1, the lowest $(H/C)_E$ ratio of 16, and the highest $(H/C)_c$ ratio of 90. Surprisingly, the lower limit for the fraction of comet-derived volatiles turns out to be 0.79! All other combinations of hydrogen/carbon ratios yield $X > 1$. Even when the carbon in the Earth's upper mantle is included to yield a hydrogen/carbon ratio of 8 (Turekian and Clark, 1975), X takes a minimum value of 0.56. Unless the hydrogen/carbon ratio for the Earth is an order of magnitude lower, or the cometary hydrogen/carbon ratio is an order of magnitude higher, we are led inescapably to the conclusion that comets provided a major fraction of the volatiles that are now in the atmosphere and oceans and bound in the biosphere and the crust. Implications for the sources of the volatiles inventories of other terrestrial planets are clear.

Organic chemical evolution and the origin of life must be bound to the origin and evolution of the atmosphere of the planet that spawns it. If comets supplied

as much of the Earth's volatiles as is suggested by these simple calculations, then comets must have made a primary contribution to the set of conditions necessary for life's origin.

IV. CONCLUDING REMARKS

Whether comets represent accreted interstellar matter or bodies condensed in the outer regions of the nascent solar system, or both, cannot be resolved at this time. Surely, however, comets contain the information that will tie them to their source region. The observable chemistry of comets suggests affinities to the chemistries of carbonaceous meteorites and interstellar matter. These similarities hint of fundamental cosmogonic relationships that remain obscured in the current state of ignorance. Thus, comets represent a poorly understood but integral link in the chain of chemical evolution of primitive matter in this part of the galaxy. They may provide the connection between solar system bodies and the interstellar environment from which all were derived.

Comets and carbonaceous meteorites are plausible sources for the Earth's atmophilic and organogenic elements. The relative abundances of these volatile elements, however, are difficult to reconcile with an origin solely from meteorite matter. Although the connection between comets and the origin of life may seem at first tenuous, the probability that they contributed significantly to the Earth's volatiles inventory suggests an essential chemical evolutionary link between comets and life. In this context, it is possible to view the cosmic "accidents" that produced a solar nebula, led to formation of Earth, meteorites, and comets, and perturbed comets into primordial Earth-crossing orbits as the earliest in the series of "chance" occurrences that led to the origin of life in this solar system.

Existing knowledge of comets is unlikely to yield further insights into the role of comets in early solar system history. More substantive chemical, isotopic, mineralogic and chronologic data having direct bearing on the issues of cosmogonic and cosmochemical importance are needed. They can be best obtained through detailed study of the physical and chemical composition of comets in a cohesive program of cometary exploration that involves remote observations from Earth and in space, in situ measurements, and study of matter collected directly from a comet and returned to Earth. Although Halley's comet offers a unique opportunity for generating widespread public interest in and support for a space mission to a comet, other comets may prove equally or more amenable to scientific study. Regardless of the ultimate choices of comets and types of comet mission, this seems an appropriate time to acknowledge again our ignorance about early solar system history and to point out areas where new knowledge about comets can give new insights into our origins.

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COMETS, CARBONACEOUS CHONDRITES, AND INTERSTELLAR

CLOUDS: CONDENSATION OF CARBON

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SUMMARY

Dark interstellar clouds are known to contain silicate particles, and
are suspected to contain graphite particles. Mantles of tarry material
condensed in circumstellar winds and/or mantles of complex organic compounds,
produced by photolysis of ice mantles in diffuse interstellar clouds, may
also be present. It is believed that in addition ice mantles of CH_4, NH_3,
and H_2O are present in dark clouds.

Direct formation of comets from such particles would result in a
mixture of dust and ice not unlike that inferred from observations of
comets, so it seems plausible that such was the case. However, the presence
of ^{13}C-poor graphite would suggest that cometary gases are enriched in ^{13}C,
contrary to available spectroscopic observations of $^{13}C/^{12}C$. As the
alternative of heating the material from which comets were made to the
point that graphite would evaporate seems implausible, doubt is thrown upon
the existence of graphite in interstellar clouds at least if it is ^{13}C-poor.
Any measurements which address the various possible forms of carbon in
comets (graphite, tars, organic molecules, methane) would help elucidate
this question, as would further measurements of $^{12}C/^{13}C$ in various gas-
phase molecules.

COMETS

All the evidence supports Whipple's theory that the nucleus of a comet
consists of a loose collection of ices and dust. Infrared observations
prove that silicate dust is present; spectroscopic observations, particu-
larly of H, OH, H_2O, and H_2O^+, indicate that water ice is a major constitu-
ent. Observations of CH, C_2, C_3, and other carbon-bearing molecules prove
that carbon is present. Analysis of the production of gas by comets

indicates that the carbon may be bound in the ice in the form of CH_4 clathrate. The fact that the cometary cloud extends to interstellar distances and that comets contain volatiles which can condense only at great distances from the sun suggests that cometary material may provide a bridge between planetary material, which condensed within the solar system, and the dust in interstellar clouds.

CARBONACEOUS CHONDRITES

The carbonaceous chondrites are characterized by low density, high carbon content (up to 5%), and a grainy structure which shows very little metamorphism. They seem to be formed of silicate and iron minerals which condensed into dust particles directly from the gas of the solar nebula as it cooled.

The bulk of the carbon in these objects is in the form of tarry material between the silicate grains. It is relatively insoluble, but the small soluble fraction has been found to contain complex organic molecules of every description, including amino acids (Anders 1971).

According to thermodynamic equilibrium calculations, various silicate and iron minerals condense out sequentially as a gas of cosmic composition is cooled (Table 1). These calculations have been very successful in accounting for the observed mineral morphology. However, the presence of carbon compounds does not follow from strictly equilibrium considerations, and the theory which accounts for them remains controversial. We will return to this topic below.

CLOUDS

Interstellar clouds come in all shapes and sizes (Figure 1). In the dark clouds, seen in photographs projected against background stars, the

Table 1. Condensation temperatures for the case C < O

Stage	Temperature (^{O}K)	Condensates	Elements Removed
1	1400-1600	$CaTiO_3$	Ti
		$Mg_2Al_2O_4, Al_2SiO_3, CaAl_2Si_2O_8$	Al
		$CaMgSi_2O_6, Ca_2SiO_4, CaSiO_3$	Ca
2	1220-1320	$MgSiO_3, Mg_2SiO_4, BeAl_2O_4$	Si,Mg,Be
3	1230	Metallic Fe, Ni	Fe,Ni
4	1210	$MnSiO_3$	Mn
5	970-1070	Alkali Silicates	Na,K,Rb
6	600-700	$FeS, NaBO_2$	S,B
7	180	H_2O	O
8	120	$NH_3 \cdot H_2O$	N
9	75	$CH_4 \cdot XH_2O$	C
10	25	Ar(solid)	Ar
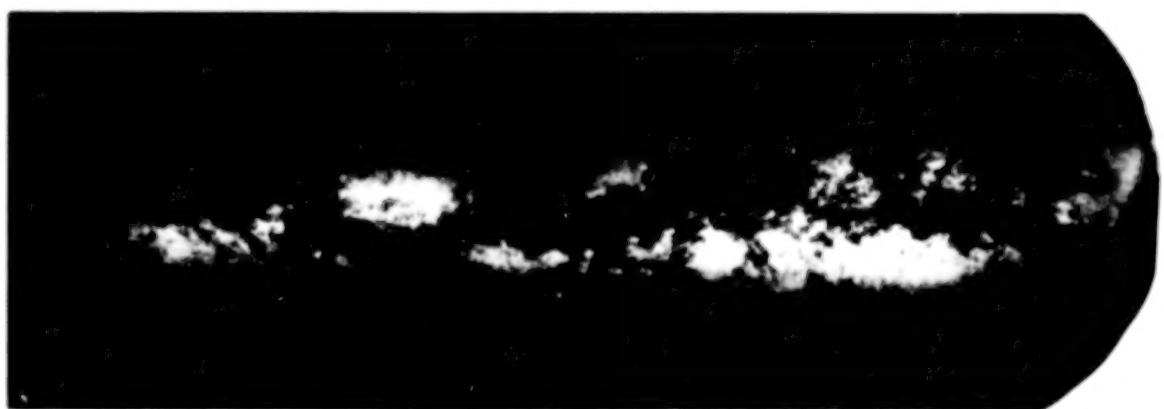
Fig. 1. A composite photograph of the Milky Way, showing the system
of stars we see passing overhead, heavily obscured at
placed by intervening clouds of interstellar dust.
(Hale Observatories)

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most abundant element, H, is in the form of H_2 molecules. Although helium and the other noble gases are in the atomic state, it is believed that most other elements are condensed into the dust particles which cause the observed blocking of starlight. A small fraction of the C, N, and O forms molecules which can be observed by the spectral lines they emit in the microwave region.

If the density of an interstellar cloud is low enough to let in starlight, however, the H_2 is photodissociated to atomic H (Spitzer 1978). Other molecules are also largely photodissociated into their atomic constituents, so radio astronomers can detect molecules in such clouds only with difficulty. On the other hand, the cloud is so diffuse that stars can be seen through it, and atoms can be detected via the absorption lines they impress on the stellar spectra.

Ultraviolet observations of diffuse clouds with the Copernicus satellite have established that many elements (silicon, magnesium, iron, calcium, aluminum, titanium) are severely depleted (10-1000 times) in the gas phase (Figure 2). This agrees well with the fact that the dust absorption exhibits a band at 10μ wavelength, as predicted for silicate dust, for these are just the elements which are expected to form silicate dust. The same silicate feature is seen in dark clouds, confirming that there is silicate dust there as well (Figure 3). The atomic depletion cannot be tested in dark clouds because ultraviolet and visible starlight cannot be seen through such clouds; however, infrared does get through, enabling us to study the 10-μ band.

Some 40 molecules have been detected in dark clouds, about 30 of them containing carbon (Table 2). CO, the most abundant, appears to contain only about 10% of the C, and other molecules are even less abundant in

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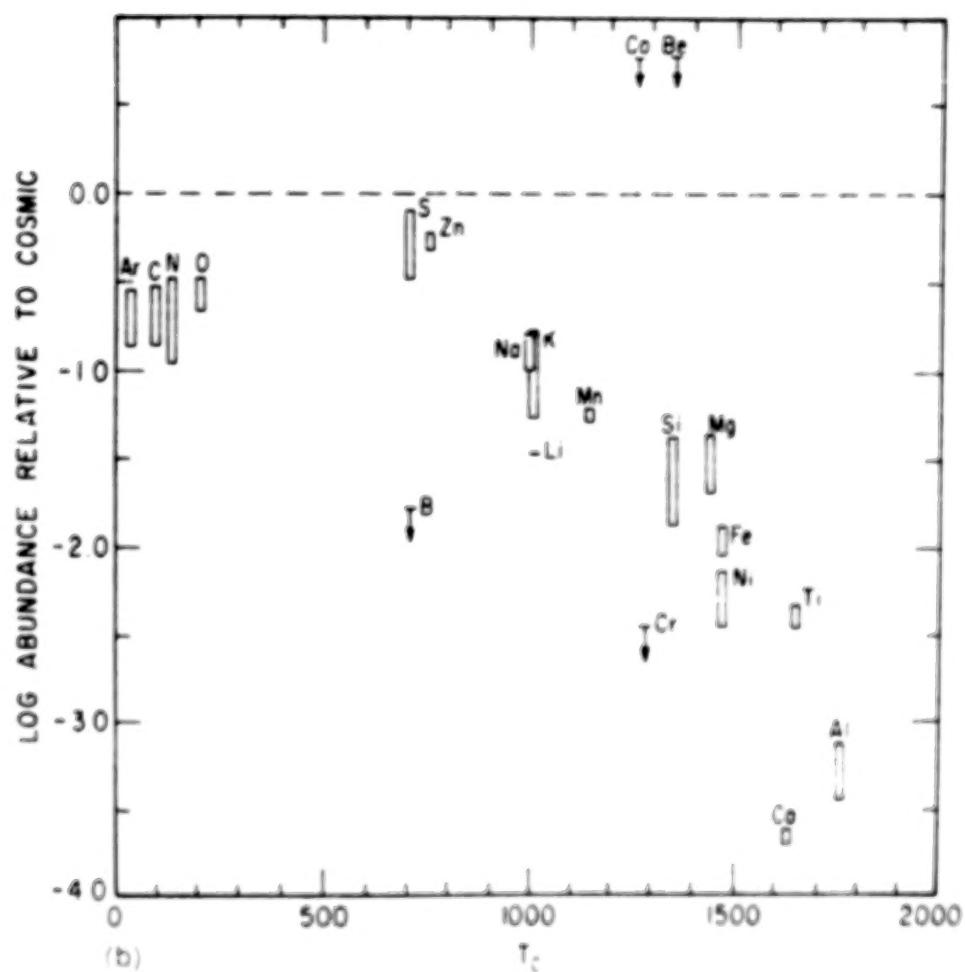
Fig. 2. Abundances of gas-phase atoms and ions in the diffuse interstellar clouds between the earth and the star Zeta Ophiuchi about 170 parsecs distant, according to studies conducted by Morton (1974) at Princeton using the ultraviolet spectrometer on the Copernicus satellite. Abundances are plotted logarithmically relative to those in the sun, so that zero ordinate (--) means normal abundances, and -1.0 means depletion by a factor 10. The abundances are plotted against the temperatures T_c at which the elements would condense out if C < O according to Table I. Note the rough correlation of the depletion factors with increasing T_c above 700°K.
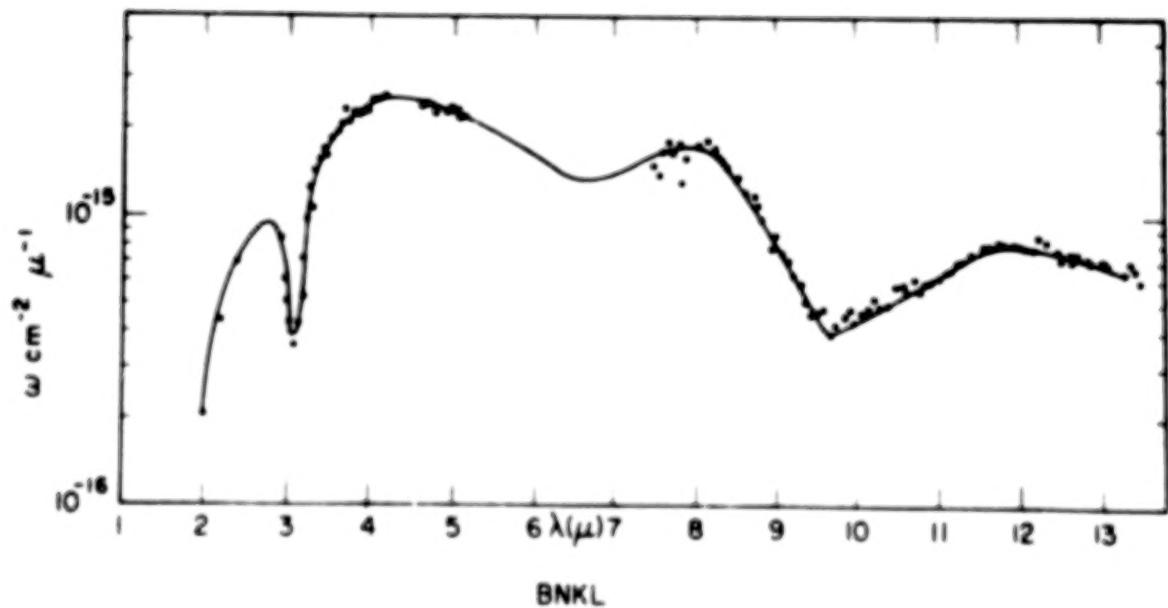
Fig. 3. The spectrum of the infrared source in Orion, showing characteristic absorption features at 3.1μ (attributed to water ice) and 10μ (attributed to silicates).

Table 2. Molecules detected in the interstellar medium as of 1977
(Field, Verschuur, and Ponnamperuma, 1978)

Observed in Interstellar Space	Name
H_2	Hydrogen
CH^+	Methyladyne ion
CH	Methyladyne radical
CN	Cyanogen
OH	Hydroxyl radical
CO	Carbon monoxide
CS	Carbon monosulfide
SiO	Silicon monoxide
NS	Nitrogen sulfide
SO	Sulfur monoxide
SiS	Silicon sulfide
H_2O	Water
HCN	Hydrogen cyanide
HNC	Hydrogen isocyanide
HCO^+	Formyl ion
H_2S	Hydrogen sulfide
OCS	Carbonyl sulfide
SO_2	Sulfur dioxide
C_2H	Ethynyl radical
N_2H^+	(Unnamed)
HDO	Heavy water
NH_3	Ammonia
H_2CO	Formaldehyde
H_2CS	Thioformaldehyde
$HNCO$	Isocyanic acid
C_2H_2	Acetelyne
$HCOOH$	Formic acid
H_2CNH	Methanimine
HC_3N	Cyanoacetylene

Table 2. Molecules detected in the interstellar medium as of 1977
(Field, Verschuur, and Ponnamperuma, 1978) (Continued)

Observed in Interstellar Space	Name
H_2NCN	Cyanamide
CH_3OH	Methyl alcohol
CH_3CN	Methyl cyanide
NH_2HCO	Formamide
CH_3C_2H	Methylacetylene
CH_3HCO	Acetaldehyde
CH_3NH_2	Methylamine
H_2C_2HCN	Vinyl cyanide
HC_5N	Cyanodiacetalyne
$HCOCH_3$	Methyl formate
CH_3CH_2OH	Ethyl alcohol
$(CH_3)_2O$	Dimethyl ether

relation to their parent atoms. While H_2 is catalyzed on grain surfaces, it is believed that most other molecules are formed by gas-phase, ion-molecule reactions involving H_2^+, which in turn is formed by the cosmic-ray ionization of H_2 (Figure 4). Chemical schemes embodying these reactions have had a number of successes, the latest being the prediction of the abundance of C_2.

CARBON IN STARS

In the solar system and in the atmospheres of normal stars, $C/H = 3.7 \times 10^{-4}$ and $O/H = 6.7 \times 10^{-4}$ (Cameron 1973). Thus, $C/O = 0.55$. The $^{13}C/^{12}C$ ratio in the solar system is $1/90$. This ratio seems to apply in many stars, but in others the ratio appears to be higher.

Carbon is produced in stars in two ways, as a byproduct of the CNO cycle in stars like the sun, and as a product of helium burning (triple α) in the hot cores of giant stars. Theoretically, these two processes are easily distinguishable: the CNO cycle gives $C < O$ and $^{13}C/^{12}C$ ranging up to $1/4$, while 3α gives $C > O$ and $^{13}C/^{12}C \ll 1$. Unfortunately, the effects of both processes are sometimes confused in the same type of evolved star, the outer layers showing the effects of an earlier CNO phase and the inner layers, exposed by mass loss, showing the effects of 3α.

Although normal stars and the interstellar medium as a whole have $C < O$, some special stars have $C > O$. Among these are carbon stars, infrared stars believed to be the precursors of planetary nebulae, and planetary nebulae themselves (Figure 5).

Thermodynamics predicts dramatic chemical effects when one switches from $C < O$ to $C > O$ because of the great stability of the CO molecule. Thus, when $C < O$ (the usual situation), cooling below about $3000°$ produces
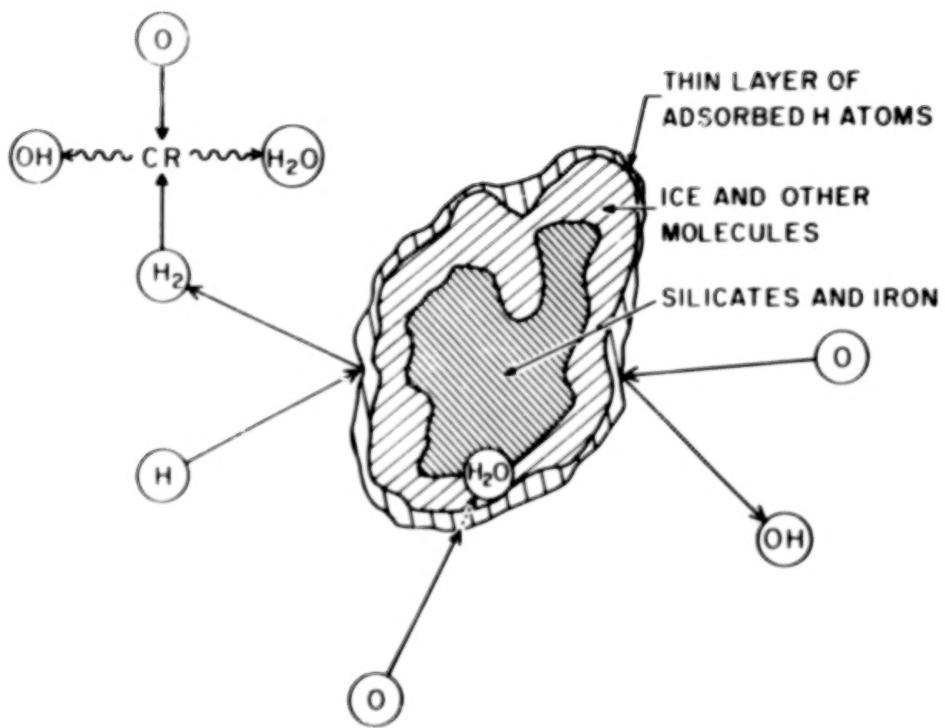
Fig. 4. An artist's conception of an interstellar grain.
H_2 is formed by surface reactions among adsorbed
H atoms, and expelled into the gas. Cosmic rays
produce H_2^+, which reacts with C, N, and O to
give OH, H_2O and other molecules of Table 2.
OH can also be produced directly by surface
reactions of O and H, and the H_2O produced in
this way (as well as CH_4 and NH_3) freezes down
to provide an ice mantle.
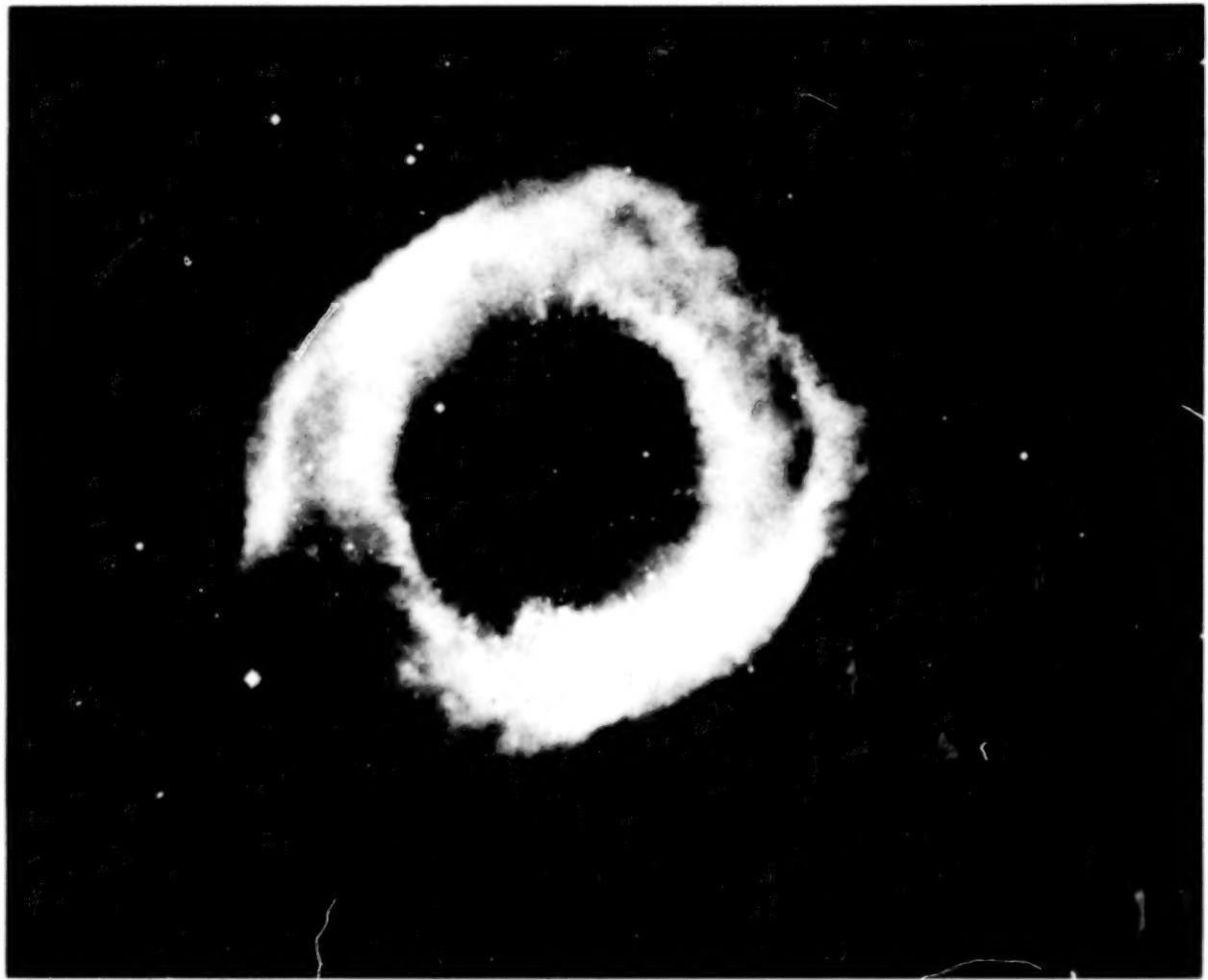
Fig. 5. A planetary nebula. The central star, a compact
hot star left over after the expulsion of the
outer layers of a giant star to form the nebula,
can be seen. (Hale Observatories)

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CO, with the extra O going into H_2O. When $C > O$, carbon is left over, and instead of H_2O, one gets carbon-bearing molecules like C_2. When the temperature drops low enough (say < 2000°), very different condensation processes occur. If $C < O$, oxygen is available to make silicates, and carbon remains gaseous as CO. If $C > O$, all the O is in CO, and the excess carbon condenses as silicon carbide (SiC) and graphite.

Both O-rich and C-rich giants have been observed to undergo mass loss. As might be expected, the cooling of the expanding gas promotes formation of dust in these cases. In the C-rich giants one sees dust, which, because of the presence of the 10-μ feature, must contain silicates. In the C-rich giants one also sees dust, but no 10-μ feature. The dust is presumed to be graphite and silicon carbide.

The interstellar medium is the ultimate repository of stellar dust. As stated earlier, silicate dust is observed to be ubiquitous there. In view of the fact that C-rich stars are observed to emit dust which is known not to be silicate, it is interesting to ask whether graphite can be seen in the interstellar medium. Graphite has no infrared features, and thus cannot be detected in the cool stars where it is believed to be forming. However, it does have a very strong ultraviolet absorption band at 2200 Å, due to transition of a π electron into the conduction band. On this basis it was predicted (Hoyle and Wickramasinghe 1962) that this band should appear in interstellar extinction. This prediction was dramatically confirmed by the OAO-2 satellite, which found that the 2200 Å band appears in nearly every star, with a strength proportional to the amount of extinction in the visible (Figure 6). From these observations one calculates (Field 1974) that in the diffuse clouds 60% of the carbon is in graphite.
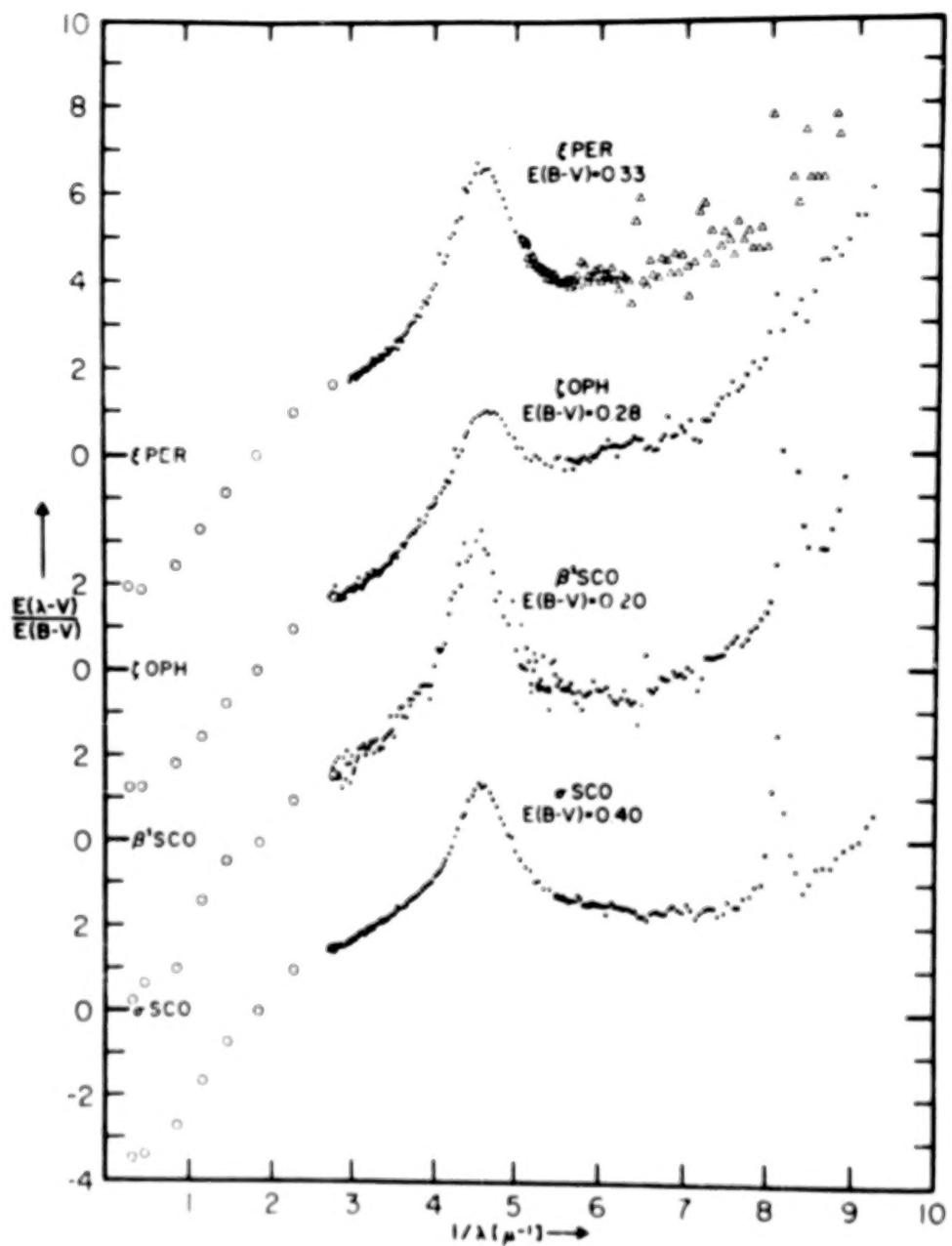
Fig. 6. Evidence for graphite in the interstellar medium. What is plotted is the attenuation of various stars, in magnitudes, against wave number in inverse microns. The absorption feature at $\lambda^{-1} = 4.5\mu^{-1}$ ($\lambda = 2200$ Å) is characteristic of graphite (Bless and Savage 1972).

CARBON IN CLOUDS

What is the state of the ∿40% of the carbon in diffuse clouds which is not in graphite? The Copernicus satellite found that, like silicon, magnesium, etc., the volatile elements C, N, and O are also depleted from the gas phase, typically by factors 3-5. Although both the graphite and gas-phase abundances are uncertain, it seems likely that carbon has condensed in forms other than graphite, as well as into graphite. As the graphite must have formed in C-rich stars, the remaining fraction must contain that carbon which was ejected, along with silicate dust, from O-rich stars. Any molecular components like CO in such ejecta would have been photodissociated as soon as the ejecta became optically thin; indeed, Copernicus observed very little CO in diffuse clouds. Two possibilities present themselves:

(i) During ejection from the star, carbon condensed onto grains in the form of the tarry material found in carbonaceous chondrites. We will discuss this process further below, but suffice it to say here that this would explain how it avoided being returned to the gas phase, as the material should be resistant to photodesorption.

(ii) Alternatively, (i) did not happen with any regularity, and the carbon was slowly accreted by the grains much later, while in the interstellar medium. This takes us back to the original proposal by Oort and van de Hulst (1946) - that the interstellar atoms of C, N, and O would stick to grains, and because of the great abundance of H, form a composite ice of CH_4, NH_3, and H_2O.

While this is an attractive picture, it must be modified to agree with current facts. First, it is known from laboratory work that such

a mixture exposed to the UV spectrum of interstellar space would be photo-lyzed in 10^6 years (Greenberg *et al.* 1972). The resulting material should contain free radicals and the products of their reactions together--organic molecules of every description. Second, and quite harmonious with this fact, H_2O ice has been sought in diffuse clouds by means of its 3.1-μ absorption band, without success; less than 10% of the O can be in this form. If the icy mixture were photolyzed, the ice band would not be present, as is observed to be the case. Against this picture, however, are calculations which show that volatiles are readily removed from silicate grains by photo-desorption. How do the ices form in the first place?

It should be noted that relatively weak shock waves occurring in the interstellar medium will result in the sputtering of a volatile mantle off the dust grains. The Copernicus satellite observations of small amounts of gas-phase C, N, and O would allow perhaps one in five clouds to have been recently processed in this way.

In summary, C (also N and O) is depleted over and above that C in graphite. It could be in the form of a tarry mantle which accompanied the formation of silicate dust, or in the form of photolyzed mantles of CH_4, NH_3, and H_2O ices. Identification of the many diffuse interstellar bands, believed to originate in the solid phase, but not so far identified with any mineral, could bear on this question, as the organic molecules postulated to be in the mantles seem to be reasonable sources for such bands.

The dark clouds are colder and denser than the diffuse clouds; molecules, once formed, are safe from photodissociation, and atoms and molecules sticking to dust grains are safe from photodesorption. Where, then, is the carbon? The opacity of dark clouds prevents complete spectroscopic studies, so we

don't know the amount of graphite or of gas-phase carbon atoms or ions. However, the masses of such clouds are so great ($\sim 10^5$ $M_\odot$) that the material in them must be the product of a large number of stars, and must be gathered in from a large region of interstellar space. Hence it is reasonable to suppose that they have formed from more diffuse material, perhaps by gravitational accretion. In the process, the graphite grains would be expected to be dragged along unchanged.

CO and other C-bearing molecules are observed, but they do not account for all the remaining C. Klemperer (1978) has pointed out that for the gas phase ion-molecule chemistry to produce the molecules we see, the gas phase must not be oxygen rich; that is, $C > O$ in the gas phase. This is an important point, if true, because it bears on the question of where the O is. In view of the fact that non-graphite C is only 1/5 of total O (40% of O.II), the removal of O must be nearly complete to drive C above O in the gas phase.

In dark clouds ice mantles seem like a good bet. Not only does photo-desorption fail to prevent them, but the H_2O ice band has actually been detected in a number of dark clouds. A plausible hypothesis would be that all the C and O which is not in CO has frozen down in a classical ice of CH_4, NH_3, and H_2O. CO itself is very volatile and is not expected to freeze down at the temperatures of the dust in dark clouds ($\sim 10°K$). Presumably the CO formed from the gas-phase C and O known to be present in the diffuse clouds at 20-40% of the total abundance.

In summary, the dust in dark clouds may well have ice mantles as well as mantles of tarry material and/or photolyzed ices carried over from diffuse clouds.

An interesting sidelight in all this is the $^{13}C/^{12}C$ ratio. As we said earlier, this ratio is expected to depend upon the source of the carbon (CNO or 3α). Normally one would expect that carbon from both sources would be well mixed throughout the interstellar medium. Observations of stars which have formed from the medium demonstrate that this is the case where different elements are involved. Hence the ^{12}C and ^{13}C in the solar system as a whole should represent contributions from both sources. As a result, the measured $^{13}C/^{12}C$ ratio in the earth and meteorites (1/90) should be indicative of the overall ratio in the interstellar medium at the time the solar system formed.

However, graphite could introduce an interesting wrinkle in this. If it formed in C-rich stars, which are carbon-rich because of 3α, it would contain little ^{13}C, so that the non-graphite fraction of the interstellar medium must contain most of the ^{13}C. If the graphite is 60% of the interstellar carbon, and if its $^{13}C/^{12}C$ is $\ll$ 1/90, the remaining fraction must have $^{13}C/^{12}C \simeq 1/36$. It is interesting that Townes (1977) in his 1976 Halley Lecture concludes from a large amount of data on carbon-bearing molecules in dark clouds that $^{13}C/^{12}C$ in those molecules is roughly a factor of two higher than 1/90. On the other hand, there is reason to be skeptical of this result. Not only are there severe saturation problems with many of the lines observed, but Watson (1973) has proposed that chemical fractionation can account for the observed effects, if real. Moreover, an optical observation of $^{13}CH^{+}$ in front of ζ Oph, in which saturation effects should be easier to account for, yields $^{13}C/^{12}C = 1/(90 \pm 30)$ (Snell *et al.* 1977). As the ratio for CO in the same star equals $1/(80 \pm 25)$ there is no direct evidence for fractionation between these molecules, while the theory suggests there should be a factor of 2 difference.

How would the lack of ^{13}C in interstellar graphite (if true) affect the solar system? Because graphite is highly refractory, it would certainly survive incorporation into cometary material, so again one would expect ^{13}C enrichment of the non-graphite fraction. Although the observations are quite uncertain and involve only one molecule (C_2) in three different comets; they all give ^{13}C/^{12}C = 1/100 (Whipple and Heubner 1976), apparently sufficient to exclude much graphite in comets if indeed it is poor in ^{13}C.

In this connection, it is interesting to inquire into the ^{13}C/^{12}C ratio in carbonaceous chondrites. The overall ratio is 1/90, although some fractionation is seen among the various molecules, which can be explained by normal chemical processes. There seems to be disagreement as to whether graphite is or is not present; if so, it is certainly a small fraction of the carbon. According to one study (Vinogradov et al., 1967), ^{13}C/^{12}C in the graphite is 1/91, not significantly different from the overall ratio. Of course, it is conceivable that small amounts of graphite formed later from the tarry material, in which case no gross effects are expected.

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CARBON IN METEORITES

This brings us to a general discussion of the carbon in carbonaceous chondrites. We alluded above to the fact that chemical equilibrium calculations yield a condensation sequence which seems to account for the minerals in the grains of carbonaceous chondrites in a straightforward way by cooling from a high temperature. However, carbon is a different story. It is found that in the presence of large amounts of H_2, the stable form of C is CO above about 600°K, but CH_4 below that temperature. As CH_4 does not freeze out until 75°K, if this were the whole story C

would be gaseous (CO or CH_4) within the inner solar system, and therefore would not have been incorporated into the terrestrial planets (or meteorites), as is demonstrated from the near absence of the noble gases from the earth. How, then, is one to account for the abundant carbon on the earth and in carbonaceous chondrites? Anders (1971) answers that although CH_4 is thermodynamically stable below $600°K$, the reaction $CO + 3H_2 \rightarrow CH_4 + H_2O$ by which it is produced from CO goes very slowly in the absence of catalysts. Suitable catalysts are not present at $600°K$, but at $350°K$, iron oxidizes to Fe_3O_4 and the silicates take on water of hydration; both products are good catalysts. However, the ensuing reactions do not reduce the carbon entirely to CH_4, but only about halfway, to hydrocarbons of the type $C_{20}H_{42}$. These latter have high molecular weight and low vapor pressure, and hence condense out on the dust particles already present in the solar nebula. The process is similar to the Fischer-Tropsch synthesis used commercially to produce gasoline. By way of proof, Anders shows that many of the compounds and their detailed properties (e.g., $^{13}C - ^{12}C$ fractionation) found in carbonaceous chondrites match very well those found in the laboratory using Fischer-Tropsch synthesis. If this is the correct picture, carbon is present on the earth only because of a quirk in reaction kinetics which produced high-molecular weight hydrocarbons instead of CH_4.

CARBON IN COMETS

What, then, of the comets? The presence of H_2O ice in them shows that they could not have accumulated at temperatures above $200°K$, or else the ice would have sublimed and been lost (as indeed it is observed to do when comets enter the inner solar system). On the other hand, we

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don't know the maximum temperature reached by cometary material. If
> 2000°K, everything would have been vaporized, and the standard conden-
sation sequence would have been followed. In this case, one would expect
at least some of the carbon to have produced a Fischer-Tropsch tar at
∿350°K. As the temperature fell, H_2O would ultimately have condensed out
as ice. It is not clear whether enough carbon would have remained to
produce the CH_4 believed to be responsible for the clathrate needed to
explain the observed properties of comets. In this model, perhaps even
the graphite would have been vaporized, and so no gross anomalies in
$^{13}C/^{12}C$ would be expected.

Suppose, on the other hand, that the highest temperature is in the
range 500° - 2000°K, say. Then the refractories (including graphite)
in the interstellar dust would have survived, while the volatile mantles
(be they tar or ices) would have evaporated. In this case, Fischer-Tropsch
would again produce tar, but its $^{13}C/^{12}C$ would be anomalous; when CH_4 freezes
out at lower temperatures, its $^{13}C/^{12}C$ would be anomalous also. The spectros-
copic observations of $^{13}C/^{12}C$ in comets argue against this case.

If T_{max} is in the range 200 - 500°K, the tars as well as the refrac-
tories would survive, but ices would have evaporated, only to recondense
when T dropped below 200°. The $^{13}C/^{12}C$ ratio is still inconsistent with
observation.

Finally, if T_{max} < 200°K, even H_2O ice would survive, and if T_{max} is
low enough, CH_4 ice would also. Because these substances are expected to
be major components of dense interstellar clouds (see above), cometary
material would be expected to be a mixture of ice and dust, as is observed.
Again, however, the $^{13}C/^{12}C$ ratio would be anomalous, contrary to
observation.

If one takes these considerations seriously, only the high-temperature model is allowed; only in that model is the graphite vaporized and its low ^{13}C content distributed. However, there are severe objections to the high-temperature model. According to models of the solar nebula, high temperatures never prevailed outside the inner solar system. Hence, the high-temperature scenario requires that comets form in the inner solar system, and hence have small perihelia. But then they would long ago have become periodic or hyperbolic as a result of planetary perturbations. Instead, it is believed that the comets formed far from the sun, where the temperatures are low, and that the long-period ones are entering the solar system for the first time as a result of stellar perturbations. Thus, one would expect them to consist of unprocessed interstellar grains, which as we have seen should be a mixture of silicates, graphite, and mantles of tar and ice. This seems to accord well with what we know about comets, with the exception of the $^{13}C/^{12}C$ ratio.

What, then, can we learn about interstellar dust from the study of comets? I suggest two lines of inquiry:

1) Is there really graphite in the interstellar medium after all? Even though it is predicted from thermodynamic calculations, its existence in carbon-rich stars is inferred from observations of dust, and its predicted UV band is present in diffuse clouds, there are nagging doubts. It is worrisome that the UV band is not seen in planetary nebulae. This can be explained if the particles are large ... (>0.04μ; Mathis 1978), but the presence of the band in diffuse clouds requires that they be smaller than that; hence some fragmentation process is necessary. Not only that, but it has been shown that to reproduce the shape of the band observed in diffuse clouds, the graphite particles must be spherical and free from

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accreted mantles (Gilra, 1971). Both conditions are hard to accept. Finally, alternative identifications exist, as apparently 2200 Å is commonly associated with an unpaired π electron in various organic molecules. Most recently, polysaccharides have been suggested in this connection. All these doubts suggest that graphite is actually only a minor constituent of interstellar clouds, and thus, of comets. If this is true, the spectroscopic observations of $^{13}C/^{12}C$ in comets are readily understood.

2) Leaving aside graphite, in what form _is_ the carbon in comets? Here the natural choices are CH_4, already indicated by gas-production studies, and possible Fischer-Tropsch tars. If T_{max} was less than 400° (as seems likely), then such tars could be primordial, and very interesting clues to the conditions under which the dust formed. Also, remember that photolysis is expected to have converted at least some of the icy mantles present into complex organics, perhaps similar to, perhaps different from Fischer-Tropsch tar. This would be of great interest in assessing the history of interstellar dust. Thus, it would be very interesting to get a handle on the form taken by carbon in the nucleus of a comet.

3) As a subsidiary problem, the $^{13}C/^{12}C$ ratio is of interest, because the spectroscopic value is uncertain. Also, it would be of interest to extend our knowledge to other constituents like CO_2, which could originate in a different fraction of carbon.

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SCIENTIFIC RETURNS FROM A PROGRAM OF SPACE MISSIONS TO COMETS

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ABSTRACT

Cometary science is potentially at the crossroads of several inter-disciplinary connections that have not been developed, only because our present knowledge of comets is incomplete or, at best, semi-quantitative.

The scientific return of a program of cometary missions would conceivably improve our understanding of most of the following topics: nature and size of interstellar dust, its origin and evolution; identification of new interstellar molecules; clarification of interstellar chemistry; accretion of grains into protosolar "cometesimals"; role of a T Tauri wind in the dissipation of the protosolar nebula; record of isotopic anomalies, better preserved in comets than in meteorites; cosmogenic and radiogenic dating of comets; cosmochronology and mineralogy of meteorites, as compared with that of cometary samples; origin of the earth's biosphere, and therefore the origin of life. Many unsolved problems related to cometary phenomena may also receive a final answer, like the understanding of the ionization mechanisms in comets, or the behavior of magnetized plasmas in space.

Such a cometary program would typically require about three rendezvous missions of progressive complexity; for instance, the second would require a successful docking, the third a sample return. If such a program is to be attempted before the end of this century, not many opportunities are available. Comet Halley is by far the best target for a first comet mission. It has a fairly reliable brightness and orbital behavior and has a gas production rate two orders of magnitude greater than any other comet whose passage can be reliably predicted before 2010. For this reason, more accurate and sensitive measurements of its chemical compo-sition are possible. It is also the only reliable comet to display the full range of cometary phenomena.

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Although two orders of magnitude fainter, many of the very short-period comets (there are 35 of them with periods from 3 to 7 years) have the orbital reliability for other cometary missions. In particular, although the production rate of gases of Comet Encke has considerably decayed during the last centuries, it still seems to have a rather large (kilometer-size) solid nucleus. Some of the most important records of past events could be more erased on Comet Encke than on Comet Halley; yet, a thin outer crust might protect pristine material that could be reached by digging. As an example of a very short-period comet with a reliable orbit, Comet Encke is therefore a good candidate for a sample-return mission, if it is preceded by an exploratory docking mission. However, in the present state of our ignorance, none of the other very short-period comets could be rejected as a scientifically less acceptable target for such a mission.

A program of space missions to comets may be justified by both strong scientific and public appeal. For this reason, before speaking about its ientific returns, I'd like to say a few words about its public appeal.

I perceive the public appeal of space exploration at two different levels -- the conquest of space for adventure and the search of the unknown for mystery. Let me first expand somewhat these two ideas as far as comets are concerned.

Conquest of Space for Adventure

As part of my duties at The University of Toledo, I give a class of Descriptive Astronomy for Non-Science Majors. Some of my students, who are fans of Star Trek and Star Wars, have told me that the expansion of mankind to all habitable worlds is the only legitimate final goal of space exploration. Space colonization is the last frontier for the young conquistadores of the 20th century, and to them, comets do not look very habitable. I told them that they were misinformed; on the contrary, the cometary environment may be the ultimate best place to develop space colonies. We will find there an abundance of all those chemicals needed to sustain life, already in almost the right proportions, because the H, C, N, and O atoms, which are the four basic constituents of our bodies, make up half of the cometary stuff.

However, even when we are ready for space colonies (it won't be before the 21st century anyway), they may become indeed an important by-product of space exploration, but I do not believe that they could ever become its final goal.

Search of the Unknown for Mystery

In hindsight, the colonization of the Americas was possibly a by-product of the renaissance, but the major achievement of the

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renaissance men was rather an expansion of knowledge yielding a better understanding of the nature of man. In the same way, our scientific and technological revolution has done it all over again on a grander scale, and the quest for relevance of the younger generation is nothing else but the first signs of a new world culture trying to integrate an expanding awareness of the world around us.

I therefore believe that, in our post-industrial society, our search for more basic values cannot do anything but grow, and the most fundamental question which transcends the colonization of space will remain the understanding of man. For this reason, the strongest public appeal of NASA's planetary exploration program will remain based on the search of the unknown, for mystery; and its ultimate goal will be to extend our awareness of what we are, in particular, to throw some light on the possible meaning of our presence in this corner of a forever very mysterious universe.

In the specific context of the planetary exploration program of the 1980's, I believe that the major mystery, that which has the strongest public appeal, is the question of how and why life appeared on the Earth, where it has (or could have) happened elsewhere in the planetary system, and whether the conditions needed to make life appear on the Earth were a natural and automatic consequence of the origin and evolution of the solar system.

In spite of the fascinating interest of the Viking landers' findings on Mars, they have brought, rightly or wrongly, a kind of anticlimax to the laymen's hopes of finding clues about life and its origin within the solar system. Those who believe in this anticlimax have certainly not pondered about what we are beginning to guess about comets. First,

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among the heavenly bodies, comets seem to contain the largest fraction (about one half) of H, C, N, and O molecules, already in almost the right proportions for life. Second, their analogy with carbonaceous chondrites suggests that they, also, contain prebiotic amino-acids (contrary to the Martian soil). Third, their highly elliptical trajectories introduce wide fluctuations in their crust temperature and in their ultraviolet irradiation, which may be the prerequisites needed to induce a prebiotic evolution. The crucial step from amino acids to viruses is the one we understand the least, and it is not unlikely that it could be somewhat clarified by cometary exploration. Fourth, it is not unlikely that a comet bombardment of the primitive Earth was the major or the only source of the biosphere (atmosphere, oceans and soil). Fifth, if comets were the source of the early life on Earth, it is not unlikely that this source of life has not dried up, and is still operating under our unsuspecting eyes. NASA's U-2 aircraft has collected cometary dust floating gently in the upper atmosphere, demonstrating that right now, cometary viruses could easily survive an atmospheric entry. Hoyle and Wickramasinghe (1977) have been bold enough to propose this chain of speculations and they are now checking the possibility that previously unknown viral infections have been periodically brought about by cometary dust. This conjecture gives a new dimension to the sudden world appearance of a new type of flu (that has been repeatedly observed) and a new twist to the medieval belief that comets are bad omens! Even if speculations of this type are not easily accepted by the scientific community, they play an important role in exploring the limits of our knowledge and in inducing the checks and balances needed to improve the paradigm of accepted science.

"New" Comets are the Most Pristine Bodies of the Solar System

Before reviewing the scientific returns from a program of space missions to comets, it is proper to summarize first what we know about comets.

The spectacular display of a comet's tail--that can be occasionally larger than one hundred million miles--is produced by the decay in the solar heat and light of a tiny object (tiny at least for astronomers) that we call the cometary "nucleus." It may be a couple of miles in diameter, and it can be described as a cold mixture of dust and snows, not only of water snows, but also snows of solidified gases of a gamut of volatile molecules mainly made of hydrogen, carbon, nitrogen, and oxygen. In short, the cometary nucleus is a "big dirty snowball." We have observed more than six hundred different comets so far, and we believe that there might still be billions of them, bound to the solar system but too far away to be directly detected.

Based on orbital as well as on abundance considerations, cometary nuclei are believed to be the most pristine bodies still around in the solar system, which makes them the probable building blocks from which most or all of the planets have been made.

Let's first summarize orbital evidence. The primary source of comets (see Fig. 1) seems to be a big reservoir gravitationally bound to the solar system which therefore participates in its motion--the Öpik-Oort cloud. We have observed so far approximately 100 "new" comets, coming straight from this cloud (transit time: 2 to 5 million years), but we have become progressively convinced that all secondary sources of comets are derived from this primary source. The 440 long and intermediate-period comets observed so far (periods from 200 years to more than 1 million
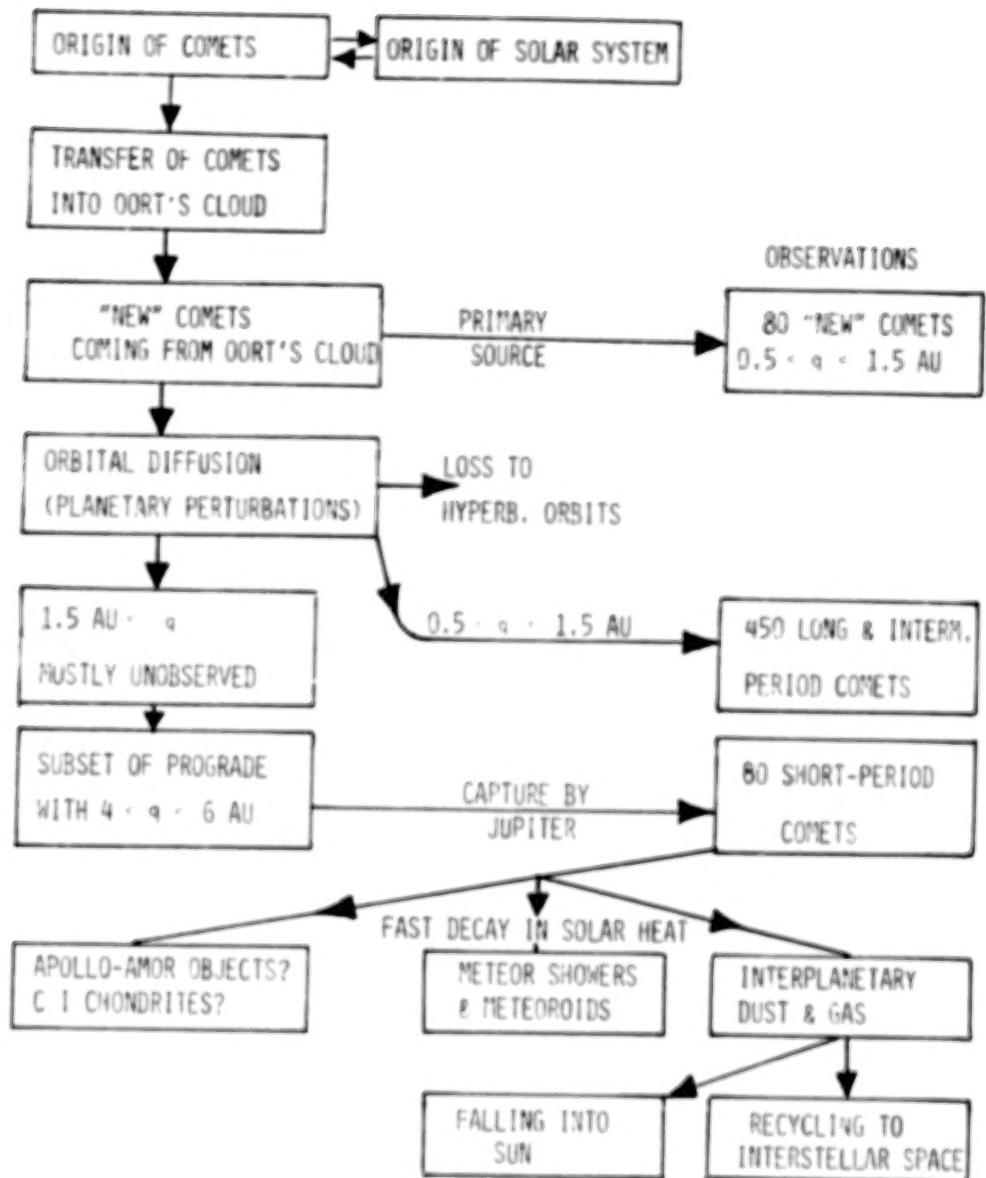
Fig. 1. The origin and evolution of comets--orbital evidence.

years) come from the orbital diffusion of "new" comets, induced by planetary perturbations. The 100 short-period comets have been captured from an unobservable subset induced by the same orbital diffusion: this subset includes those prograde comets whose perihelia are in the vicinity, mainly, of Jupiter (secondarily, of Saturn), so that these comets are easily captured by the giant planets. These three classes of comets all dec rapidly in the solar heat and either leave inactive comet nuclei, probably represented by the Apollo/Amor objects, stored on unstable orbits that eventually hit a terrestrial planet, or they decay into gas and dust. The dust eventually falls into the sun or is recycled to interstellar space, depending on its size.

Gas density is extremely low in the Öpik-Oort cloud. No model has ever been described in which its density could become high enough to accrete cometary nuclei in reasonable times. However, since comets are gravitationally bound to the sun, we believe that their origin is closely connected in time and space to that of the planetary system and that a mechanism of some sort must have transferred the newly-born comets into the Öpik-Oort cloud where these pristine objects have been stored until now--in the deep freeze of space.

A Possible Scenario of the Origin of the Solar System

Let's look more closely into the problem of the origins (Fig. 2). At this stage, all our scenarios are uncertain and can be contested. To simplify my discussion, I will stick to a plausible scenario, and will neglect some of the recent variations proposed by Cameron. If the solar system was formed by the contraction of an interstellar cloud, the interstellar grains present in the cloud followed suit and were covered by HCNO ices when the cloud became cold and opaque, but the subsequent

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MOLECULES AND GRAINS: FORMATION IN INTERSTELLAR SPACE (ALSO: EJECTION BY STARS)

CONTRACTION OF INTERSTELLAR CLOUD INTO SOLAR NEBULA

STRONG ◄——— THERMAL PROCESSING ———► WEAK OR NIL

ICY FRACTION LOST SILICATE GRAINS REMAIN

HCNO ICES REMAIN WITH SILICATES

– – – – – – ACCRETION – – – – – – –

PLANETESIMALS (ASTEROIDS)

COMETESIMALS (PRISTINE COMETS)

– – – – LAST STAGES OF ACCRETION – – – –

TERRESTRIAL PLANETS

ACCRETION OF H_2 + He

GIANT PLANETS

EJECTION OF MINOR BODIES BY GIANT PLANETS' PERTURBATIONS AS BY-PRODUCTS OF THEIR ACCRETION

COLLISIONS WITH TERRESTRIAL PLANETS

ASTEROID POPULATION DEPLETED

COMETS STORED INTO OORT'S CLOUD AND DEPLETED

VENEER OF COMETARY HCNO ON TERRESTRIAL PLANETS

ORIGIN OF LIFE

Fig. 2.   The origin and evolution of comets--physical evidence.

heating of the cloud from its final contraction processed the icy grains. Some which were probably totally vaporized are now in the sun. Some which were heated enough to lose their icy mantles were accreted in rings within the mid-plane of the nebula and, because of gravitational instabilities, formed those planetesimals that accreted eventually into the terrestrial planets. Those icy grains that were not heated enough to lose their icy mantles, presumably those in the outer parts of the nebula, formed cometesimals (or pristine comets), containing roughly as much HCNO molecules as metallic silicates--in other words as much volatile snows as non-volatile dust. These comets were assumedly the building blocks of the giant planets, at least Jupiter and Saturn, with a supplementary accretion of those gases still available in the solar nebula. Maybe the accretion of Uranus and Neptune took too long, and the gaseous nebula had totally dissipated before the final stages of their accretion; but this is another problem.

The important fact is that in this scenario, the Öpik-Oort cloud becomes a necessary consequence of the accretion mechanism. As soon as the giant planets developed a gravitationally significant core, they ejected minor bodies out the solar system and caused cometesimals to be stored in the Öpik-Oort cloud. Ejected at random, a good fraction of these cometesimals passed through the inner solar system, and their collisions with the terrestrial planets built a veneer of cometary HCNO on these planets.

In a recent review paper, Anders and Owen list many clues showing that the veneers on Earth and Mars came from the same "objects," whatever they are. The closest objects handy in our museums are the C3V carbonaceous chondrites; Anders and Owen were, of course, not able to compare

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the postulated objects with comets, because we don't have comets in our museums. Their study used a powerful tool developed for meteorites—comparing elementary abundances with solar abundances and deducing the history of the depletions from the volatile properties of the elements and of their chemical compounds. We cannot yet do that for comets, but we are not far away. I have recently (see Table 1) presented evidence that comets have kept much more volatiles than any other body of the solar system, if we exclude the giant planets where gravitation has probably played a large role.

Comets and the Origin of Life

As a matter of fact, the HCNO abundances in comets (Table 1) seem to be in the same general range as that needed to develop the delicate chemistry of life; in particular, it seems an excellent mixture to make amino acids. In Table 1, I have represented life by the standard chemical analysis of protoplasm, normalized for oxygen = 10 (I could not use silicon for normalizing, since we do not have silicon in our bodies). I believe that in particular, there is too much hydrogen to initiate life easily in the giant planets, whereas there is not enough hydrogen and too much oxygen in the crust of the Earth and of Mars. It is much easier to build up the delicate and fragile molecules needed for life by starting with a mixture about in the right proportions; of particular importance is a well chosen redox ratio (oxygen-to-hydrogen ratio), especially when dealing with solutions in water, as in the primeval oceans. In this respect, comets and carbonaceous chondrites seem to be much better sources for the biosphere (oceans and atmosphere of the Earth) than is Jupiter's atmosphere or the crust of the terrestrial planets.

Table 1. ELEMENTAL ABUNDANCES IN SOLAR SYSTEM (NORMALIZED TO SILICON = 1)

	ATMOSPHERES OF LARGER OBJECTS		SMALLER OBJECTS			LIFE*****
	SUN JUPITER? SATURN?	URANUS NEPTUNE	COMETS ***	C I CHONDRITES ****	EARTH'S CRUST	PROTOPLASM
H	30,000	100*	15	1.5	0.04	27.2
C	13	2**	3	0.7	0.02	2.1
N	3	?	>0.1	0.05	0.0001	0.3
O	21	?	21	7.5	2.8	10.0
Si	1	1	1	1	1	----

*Polodak (1976), consistent with **Owen and Cess (1975)

***Delsemme (1977); ****Mason (1971); *****Normalized to oxygen = 10

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Do comets contain amino-acids? Nobody knows, but from the present data on C I chondrites, it is tempting to predict they do. We do not know much about comet chemistry, because even under the best conditions, we have never seen a comet nucleus as more than a pinpoint of light.

In the cometary spectra, we do not see the molecules that sublimate from the nuclear ices, but only those fragments, atoms and radicals, left over from their violent interaction with sunlight and the solar wind (Table 2). Only recently has radio astronomy been able to detect parent molecules, namely HCN, CH_3CN, and H_2O; and in Toledo, we have developed circumstantial arguments suggesting that CO_2 is also one of the major constituents. However, we are far from getting accurate quantitative analyses.

Aging and Decay of "New" Comets

Now, only "new" comets, coming straight from the Öpik-Oort cloud can be guaranteed to be primitive objects with a pristine surface. Unfortunately, we cannot use them for a cometary mission, because we discover them perhaps six weeks, or at best six months, before their first perihelion passage.

Oort has established (Fig. 3) the only clear-cut differentiation linked with cometary aging and decay. The average exponent in the law relating cometary brightness to radial distance from the Sun grows with age. When combined with the sublimation theory of the nucleus, the exponent tells the average temperature of sublimation, which remains nearly constant for a particular comet. In turn, the temperature can be related to the fractional distillation of the snows in the upper layers of the nucleus. Do not forget, however, that the nucleus may remain extremely cold inside, and that pristine interstellar grains might possibly be

Table 2a.   OBSERVED CONSTITUENTS IN COMETARY HEADS AND TAILS

ORGANIC: C, C_2, C_3, CH, CN, CO, CS, HCN, CH_3CN;

INORGANIC: H, NH, NH_2; O, OH, H_2O, S;

METALS: Na, Ca, Cr, Co, Mn, Fe, Ni, Cu, V, Si;

IONS: C^+, CO^+, CO_2^+, CH^+, CN^+; N_2^+; OH^+, H_2O^+; Ca^+

DUST: Silicates (Infrared Reflection Bands)

Table 2b.   REPORTED NEGATIVE RESULTS (MAINLY RADIO SEARCHES)

ORGANIC: H_2CO, CH_3OH, CH_3O-CH_3; $CH_3-C \equiv CH$; CH_4 (Infrared)

ORGANIC WITH N: HNC, HNCO, $CH \equiv C-CN$, $CN-CH_2-CN$,

INORGANIC: NH_3, SiO_2

(Source: Delsemme (1977) supplemented by recent UV results
           from Comet West)

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I   DIFFERENTIATION WITH AGING,DETECTED BY
     BRIGHTNESS DEPENDANCE ON DISTANCE :

     B   REDUCED BRIGHTNESS (FOR: Δ = 1 A.U. FROM EARTH)
     B_0 ABSOLUTE BRIGHTNESS (ALSO: R = 1 A.U. FROM SUN)

$$B = B_0 R^{-N}$$

$\bar{N}$	ORBITAL FEATURES	TEMPERATURE	INTERPRETATION
2.8	"NEW" COMETS	110°K	SUBLIMATION CO_2
3.7	"FAIRLY NEW"	170°K	$\{$ CO_2 DISAPPEARS
3.8	"OLD" COMETS	180°K	AND H_2O SUBLIMATES
4.2	PERIODIC	200°K	$\{$ CRUST IS FORMING (ALBEDO DIMINISHES)

II   DUST / GAS RATIO   (DUST-SIZE DISTRIBUTION VARIES)

III CO^+ / (CN + C_2) RATIO   (IONIZATION EFFICIENCY IS SIZE-DEPENDENT)

Fig. 3. Physical differences among comets.

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found by digging a couple of feet into the most extinct comets. However, "new" comets display a full range of phenomena that are sometimes, but not always, found in periodic comets.

Possible Choices for a Cometary Mission

Although a periodic comet, Comet Halley does show this full range of phenomena--dusty tail, plasma tail, C_2 + CN coma, "activity," expanding halos, etc. In the present state of our ignorance, we believe that these signs mean that Halley still is a rather young comet, if not pristine. We believe it is the best choice for a first cometary mission because we can rely on its orbit and because it is much brighter than some other opportunities, such as Giacobini-Zinner, Tempel 2, and Encke. For instance, we believe that Comet Encke is a very old comet, since its steady decay has been observed during the last two centuries, but we have no way of deciding whether the scientific return of such a mission would be marginally or considerably lower than that of a mission to Halley; lower production rates may mean that a smaller number of minor constituents would be detected by our instruments.

Scientific Return of a Mission Program

Let's consider in detail what would be the scientific return of a cometary mission program. I say a mission program because I believe that, in order to achieve a large fraction of the objectives I am going to discuss, we need at least two and probably three missions, including one or two successful dockings with the nucleus and one sample return of snow and dust. If we do that, we'll have so many new answers and so many multidisciplinary connections, that the traditional problems of cometary physics may become passé and insignificant. For this reason,

I want to use the unconventional approach of ignoring the traditional problems in the first place, in order to open all interdisciplinary connections first.

Let's get started with interstellar dust and gas (Table 3). We can reasonably assume that comets still contain interstellar grains. Therefore we can gain some insight on the nature and size of interstellar dust (including its icy mantle). We can also hope that some record of the dust's origin has been preserved in grains, for instance through some isotopic ratios; this would tell us the story of its origin. Depending on the depth at which we collect the dust, we might find variations in the aging of the grains, in particular in their icy mantles. A record of cosmic-ray damages may be preserved in the first few feet of crust of any comet nucleus. This will possibly explain the chemical nature of the triggering of the activity phenomena in comets.

I will not discuss in detail the use of the proposed instruments that I have included in Tables 3-6 (those that are unlikely to be included in a first mission are in parentheses). You should however notice that the neutral mass spectrometer (for the volatile fraction-- all HCNO molecules and isotopes) and the x-ray fluorescence spectrometer (for the metals present in the non-volatile fraction) appear again and again, which demonstrates their fundamental and unique importance (with imaging) in the rendezvous mission, before any docking or sample return. We should not forget to add the interstellar molecules to this picture, since we are likely to detect those major interstellar molecules that the radio astronomers have missed so far, just, for instance, because (like CO_2) they cannot be detected by their radio spectrum. Quantitative

Table 3. INTERRELATIONS BETWEEN INTERSTELLAR AND COMETARY GRAINS

SCIENCE OBJECTIVES	ASSUMPTIONS
Nature and size of interstellar dust	Comets still contain interstellar grains
Origin of dust (In stars? In space?)	Record of dust origin preserved in grains
Evolution of dust (Aging of icy mantles)	Record of cosmic ray damages, preserved in surficial ices
Age of cometary grains	Isotopic ratios change with galactic age

INSTRUMENTS NEEDED	SCIENCE RETURN
Dust particle counter and analyzer	Dust mass distribution; dust composition
Orbital x-ray fluorescence and collected dust analyzer	Element abundance ratios for non-volatiles
Neutral mass spectrometer	a) Element abundance ratios for H, C, N, O b) Isotopic ratios c) Volatile molecule identifications

HOPES:

1. Identifying new major interstellar molecules.
2. Starting quantitative interstellar chemistry.
3. Clarifying its conceptual basis.

analyses of cometary ices would form a foundation for quantitative inter-
stellar chemistry, whose present conceptual basis is still shaky.

Another interdisciplinary connection is that of meteorites (Table 4).
Meteoritics has been extraordinarily successful because there were samples
in our museums. We could do the same with comets if we brought back a
spoonful of cometary dust and snows. The analogy between comets and
carbonaceous chondrites as given by Herbig is well known: if a C I
chondrite were put in space, vaporization by solar UV would yield all
the radicals observed in comets. Of course this is only a qualitative
statement. Quantitatively I have recently shown that comets are more
pristine than C I chondrites because they contain 3 to 10 times as much
HCNO molecules (Table 1). Therefore I believe that all techniques
developed for meteorites like cosmochronology, mineralogy of samples,
etc. will work successfully for cometary samples. We can probably do
even better: the record of the origin of the anomalous isotopic ratios
must be better preserved in comets, because less fractionation took
place, mainly for the important H, C, N, O atoms, that are one half or
more of the cometary stuff. And here, we certainly should not neglect
the prebiotic chemistry, that seems guaranteed to work in comets because
we have the proper HCNO ratios, in particular the proper (so important)
oxydo-reduction ratio.

Let's consider now (Table 5) the interrelations with the protosolar
nebula; we have two hypotheses that seem to disagree completely. Either
the cometary ices came from the icy mantles of interstellar grains or
they condensed later on the sandy grains that were the high temperature
condensates of the solar nebula. A third possibility exists that has
never been clearly expressed--the icy mantles were not destroyed but

Table 4.   INTERRELATIONS BETWEEN METEORITES AND COMETS

SCIENCE OBJECTIVES

To explain the apparent
analogy with meteorites

Origin of isotope
anomalies

Cosmochronology
Mineralogy

ASSUMPTIONS

The analogy with C I
chondr tes is not
coincidental

Record of isotope origins
better preserved in comets

Techniques developed for
meteorites will work for
cometary samples

INSTRUMENT NEEDED

Neutral mass spectrometer

Orbital x-ra fluorescence
collected dust analyzer

(On-board mineralogy)
(Sample return)

SCIENCE RETURN

HCNO and other isotopic
ratios

Volatile molecule
identifications

Search for organic materials
detected in meteorites,
amino acids, etc.

Element abundance ratio
for non-volatiles

Classification of cometary
minerals and rocks in
framework of meteorit cs

HOPES:

1.   Prebiotic chemistry.
2.   Origin of life.

Table 5.   INTERRELATIONS BETWEEN SOLAR NEBULA AND COMETARY CONDENSATES

SCIENCE OBJECTIVES

Condensation of protosolar
nebula

Temperature of comets' formation

Nature of planetesimals

Depletion of solar nebula
(By T Tauri wind?)
(In exozone?)

ASSUMPTIONS

Comets contain those gases
that condensed onto cooler
grains from the solar nebula

Presence or absence of gases
can be used as cosmothermometer

Pristine comets are those
planetesimals from which
planets were accreted

Record of gaseous fraction
is kept by condensed volatiles

INSTRUMENTS NEEDED

Neutral mass spectrometer

IR radiometer

(On board mineralogy)

SCIENCE RETURN

1)   HCNO
2)   Isotopic ratios
3)   Volatile molecules

Temperature & emissivity
of nucleus

Comparison of high and low
temperature condensates

HOPES:

Fractionation of HCNO molecules is key to HCNO ratios used by life.

processed and modified by accretion of snowy condensates of the solar

nebula. We have a way to know: .t is to go and check with a comet.

We will settle by the same token the temperature of comet formation.

If we do not find any CO or CH_4, then this temperature was higher than

50°K. If CO_2 is present in the cometary snows, then the primeval

temperature was smaller than 100°K, etc. This will tell us the nature

of the pristine planetesimals that were rather "cometesimals," i.e., the

building blocks from which all planets were accreted. The record of the

gaseous fraction of the nebula is probably also kept by the volatiles

that condensed within the cometary nuclei; therefore we will be able to

say whether the solar nebula was differentiated before condensation and

accretion. For instance, we could unravel the history of a possible

hydrogen depletion and establish whether it was due to the violent solar

wind of the T-Tauri phase of the early sun, or rather to the rotation of

the nebula, that could induce an H_2 and He loss in an exocone analogous to

the terrestrial exosphere (Table 6). Of course, we hope that this frac-

tionation of the solar nebula by different processes which are not yet

clearly understood is the key to explain those HCNO ratios that were

needed later to get life started.

Imaging will also play a decisive role, because these pristine

cometesimals are a brand-new class of heavenly bodies that we have never

seen. Perhaps Comet Encke's crust will look much like my Figure 4

(which is, you have guessed, a picture of one of the satellites of Mars,

which have the same size as cometary nuclei) but I presume a cometary

nucleus would look much more sophisticated than this, with valleys filled

up with vaporizing glaciers, giant séracs with fragile structures defying

gravity (because the gravity at the surface of a cometary nucleus is

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Table 6. INTERRELATIONS BETWEEN COMET NUCLEI AND ORIGIN OF SOLAR SYSTEM

SCIENCE OBJECTIVES

Elucidate chemistry and
morphology of "planetesimals"

Reconstruct the accretion
history of the planets

ASSUMPTIONS

Comets are "planetesimals,"
that is, pristine building
blocks of early solar system

Comets were put in "cold
storage" in Öpik-Oort cloud,
as a residue of planetary
accretion

INSTRUMENTS NEEDED

Imaging

Neutral mass spectrometer

Orbital x-ray fluorescence;
Collected dust analyzer

Radar altimeter

(On board mineralogy)
(Sample return)

SCIENCE RETURN

Size, shape, rotation
Optical properties
Physical heterogeneities

Chemistry of volatile fraction
Isotopic ratios H, C, N, O, other

Element abundance ratios
for non-volatiles

Mass
Dielectric constant
Roughness

Nature of cometary minerals
and rocks

HOPES:

Planetesimal chemistry is key to planets' accretion.

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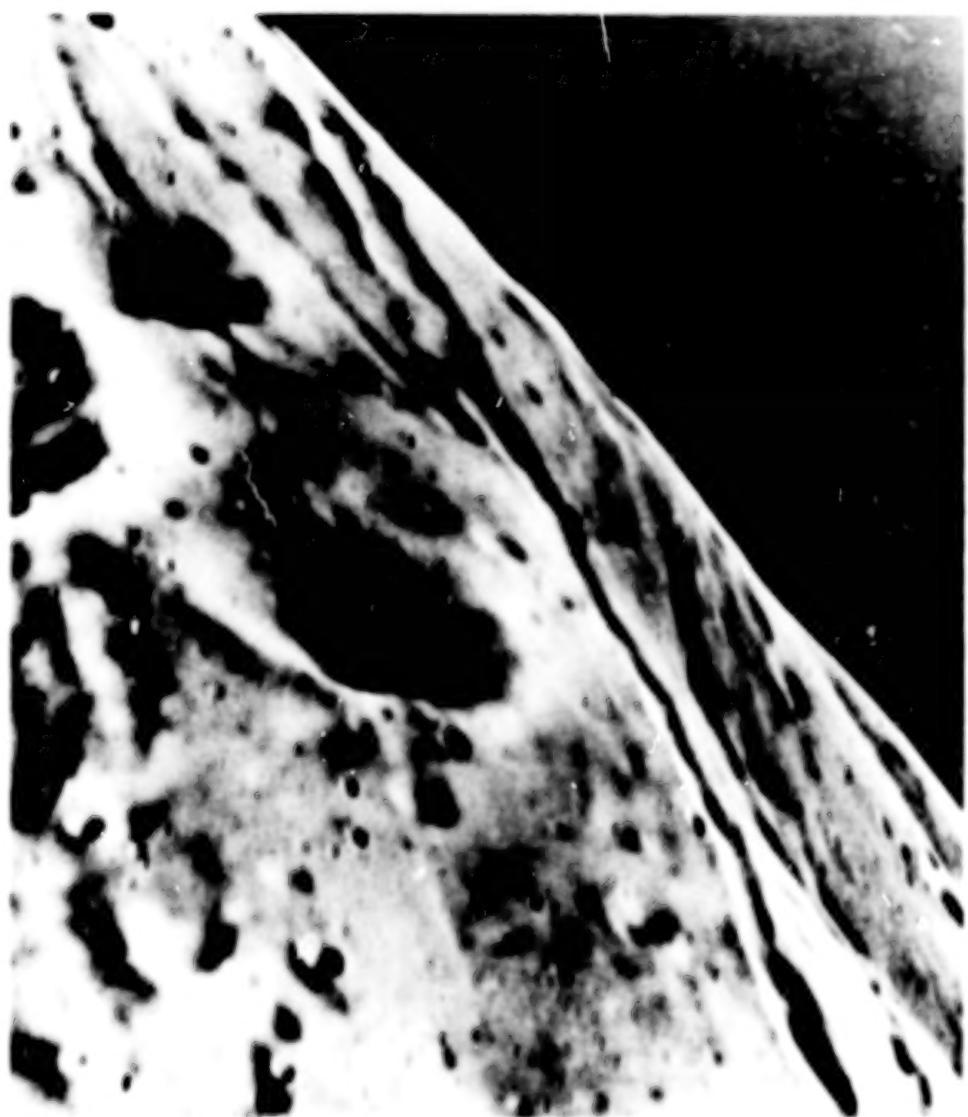
Fig. 4.   Photograph of Phobos.

some ten-thousand times lower than terrestrial gravity). But we would see a forever-changing landscape (Table 7) because the nucleus steadily decays: the atmosphere is an exosphere that drags dust away and that reaches collisionless effusion in vacuum only a few thousand miles away.

Here we reach the interrelations with meteors, meteoroids, and interplanetary dust. Is the nucleus like a raisin bread? Are the raisins going to become bolides? Do comets decay steadily into dust? Or do they build either a rocky core, or an icy core behind a crust? What is the cohesive strength of the core? What is the role of the rotation in the observed break-ups? What is the nature of the cometary outbursts? I have in Fig. 5 a list of eleven different hypotheses proposed during the last twenty-four years to explain the origin of cometary outbursts. You do not have to try to understand all these hypotheses in detail. My point is that no single convincing interpretation has been proposed so far. However, most of these interpretations are based on a structural complexity of the nuclear region which I have tried to suggest by my drawing of an outburst. This drawing is only meant to symbolize the impact that the first real picture would have, by showing for the first time an entirely unknown, new class of heavenly body. We have experienced that a few times only; you certainly remember the emotional impact when the first real pictures of Mars were substituted for the drawings of the canals of Lowell and Schiaparelli. This would be something of that order, that would enlarge our awareness and our comprehension of another facet of the universe.

Let's turn now to the study of the transient phenomena induced by the solar wind and ultraviolet light (Table 8). Cometary tails

Table 7.   DECAY AND FINAL OUTCOME OF COMETARY NUCLEI:
INTERRELATIONS WITH METEORS AND INTERPLANETARY DUST

SCIENCE OBJECTIVES

Characterize physical decay
of nucleus during passage
by the sun

Characterize final outcome
of cometary material

ASSUMPTIONS

Icy conglomerate, irregular
structure, low cohesive strength;
sublimation drags dust away

Meteoroid streams, some bolides,
and interplanetary dust are non-
volatiles lost by comets.

INSTRUMENTS NEEDED

Imaging

IR radiometer

Radar altimeter

Near IR spectrometer

SCIENCE RETURN

Disintegration of surface
Physical heterogeneities
Cohesive strength
Role of rotation in break-up
Nature of outbursts

Temperature and emissivity

Roughness and heterogeneity

Chemical homogeneity
Mineral signatures

HOPE:

Imaging a brand-new class of bodies, more primitive than planets,
that have accreted in a gravitation field smaller than 10^{-4}g.

Cometary outbursts have been alternately explained by:

1. excitation by activity outbursts of the sun (Beyer 1953).
2. vaporization of pockets of more volatile material like methane or carbon dioxide (Whitney 1955).
3. explosive radical reactions (Donn & Urey 1956).
4. excitation by corpuscular streams of the sun (Vsekhsviatskii 1966).
5. collisions with interplanetary shock waves (Eviatar et al. 1970).
6. tidal action of the Sun and Jupiter (Pittich 1972).
7. collisions with large meteoroids (Sekanina 1972).
8. cosmic rays from solar flares triggering the reaction of unsaturated hydrocarbons (Shul'man 1972).
9. transition from amorphous to cubic ice (Patashnik et al. 1974).
10. rotational breakup (Kresak 1974).
11. radiative chemical processes (Shul'man AAK 24, 91, 1975).

This mere enumeration is enough to show that no single convincing interpretation has been proposed so far.

This fanciful drawing of an outburst suggests :
a) structural complexity of nuclear region
b) impact of first actual picture of a new body

Fig. 5.   Origin of cometary outbursts.

Table 8.   BEHAVIOR OF INTERPLANETARY PLASMA

SCIENCE OBJECTIVE

Insight into all energetic
phenomena involving
magnetized plasmas

Source of ionization in
comet heads

Characterize the interaction
of solar wind with comets

Explain apparent wave motions,
twists and knots seen in tail

ASSUMPTIONS

Cometary tails are probes of
interaction of two plasmas
in conditions impossible to
duplicate in the lab

Electric currents, magnetic
fields are induced in atmosphere

There is a bow shock; there is
a contact surface; ions are
accelerated into tail

Induced by plasma interaction

INSTRUMENTS NEEDED

Thermal ion spectrometer

Ion mass and velocity/solar
wind analyzer

Magnetometer

Plasma wave detector

Electron analyzer

SCIENCE RETURN

Ionic composition, temperature
and velocity

Ionization mechanisms near
nucleus

Acceleration of ions to form tail

Bow shock, contact surface,
instabilities

Magnetic properties of ionosphere

Magnetic field of nucleus

Interaction with solar wind

Field instabilities and waves

Ionization and acceleration
mechanisms

Ionization phenomena near nucleus

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have already been used as probes of the solar wind but our models are simple-minded. We predict, but have never seen the bow shock, ahead of the comet. We could detect it easily even in a flyby mission. We also speak in terms of a contact surface which separates the cometary plasma from the solar wind plasma, but we know that cometary neutrals diffuse through it unaffected because they do not feel the magnetic field, and they can be photoionized later; therefore none of our models is satisfactory. We would like also to determine how the ions are accelerated into the plasma tail, and to explain the apparent wave motions seen in the tail; all this could be easily measured.

Fig. 6 is here only to remind you that the cometary ionosphere is a very complex animal. At this scale, the nucleus is too tiny to be seen. The center represents the zone where all atoms and molecules still collide, that is, where charge-exchange reactions take place. Practically none of the details of this theoretical model have ever been seen and identified.

Finally, I come to what the physical study of comets was all about some ten years ago, when we were using optical spectra only (Table 9). What are the parent molecules of the cometary radicals? How are they photodissociated, ionized, or otherwise transformed? How are so many ions produced near the nucleus? What are the mechanisms of decay? All of these problems would become easy if we had time sequences of mass spectrometer analyses when we were approaching the nucleus.

We must use a careful strategy that I will only briefly suggest by Figure 7. The x-axis represents the months before and after perihelion. The y-axis is the logarithmic distance to the nucleus, and I propose to move slowly back and forth to study the time variation of each observed
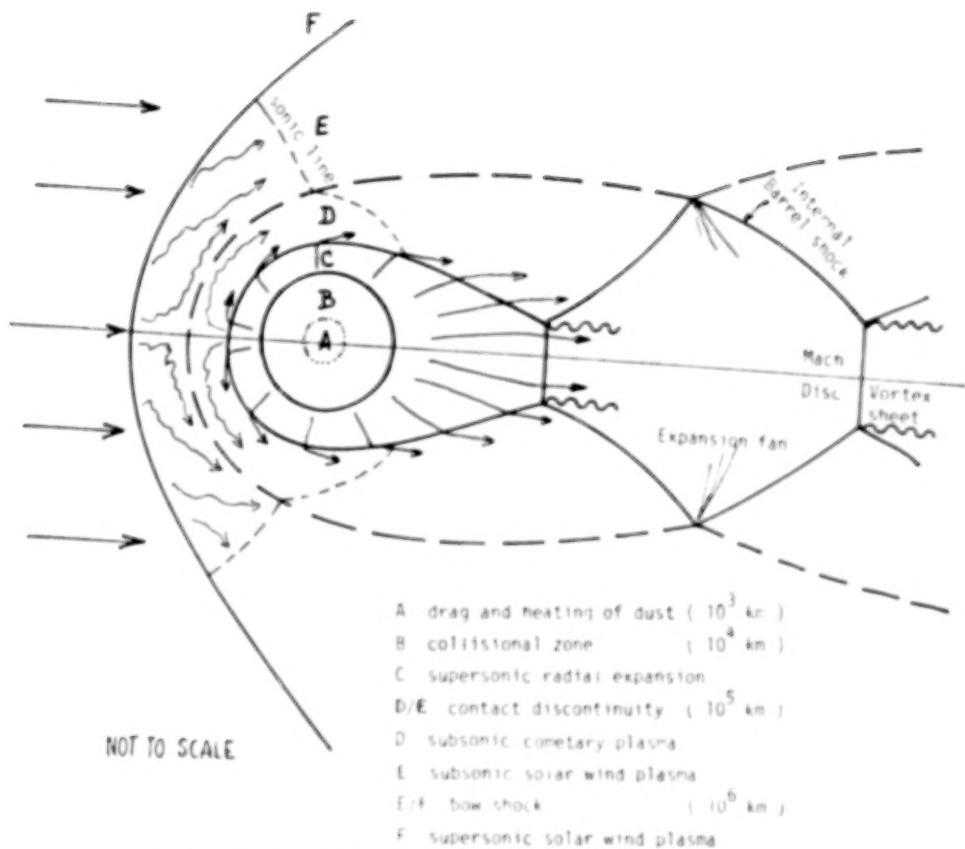
Fig. 6. Interaction of comets with the solar wind.

Table 9.   THE NEUTRAL AND IONIZED ATMOSPHERE

SCIENCE OBJECTIVE	ASSUMPTIONS
Parent molecules of observed radicals	Parents produced near nucleus by sublimation of frozen gases
Atmospheric chemistry	Charge-exchange reactions reshuffle molecular species
Ionic composition and temperature	Ions are produced very near the nucleus
Identification of ionization mechanisms near nucleus	Ionization mechanisms rely on charge-exchange reactions
Interaction with solar wind	Shock wave and contact surface can be detected by discontinuities

INSTRUMENTS NEEDED	SCIENCE RETURN
Neutral mass spectrometer	Radial variation of abundances yields understanding of coma's chemistry and ionization mechanisms
Thermal ion spectrometer electron analyzer	Ionization mechanisms
Ion mass and velocity solar wind analyzer	Ion acceleration mechanisms; interaction of solar wind; bow shock; contact surface; instabilities
UV spectrometer	Neutral and ion production rate Scale lengths of species Dust distribution and albedo
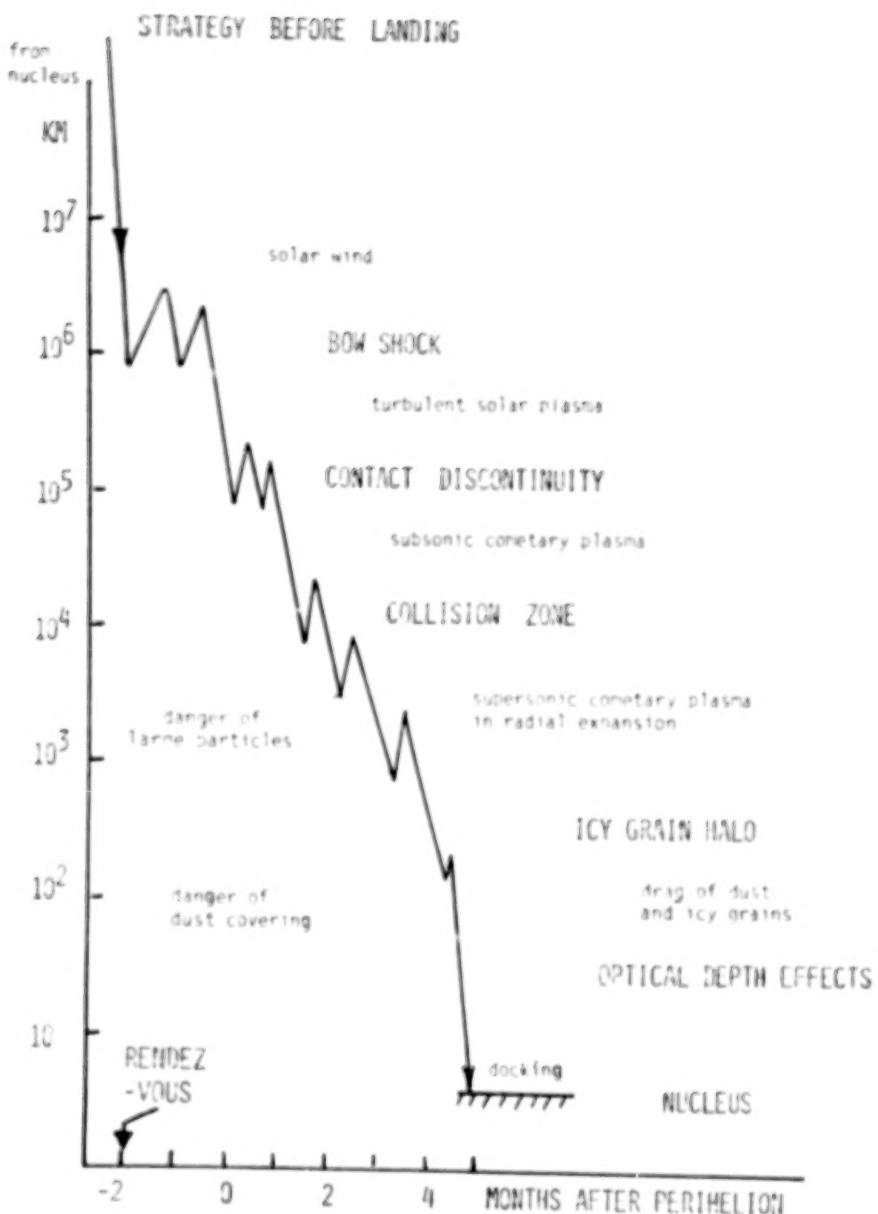
Fig. 7.   Exploration strategy before landing.

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transition or discontinuity. The nearer to the nucleus, the more exciting the results, the closer to pristine molecules, the more difficult and risky. A first rendezvous should certainly terminate by a tentative landing, or rather by a docking (landing has no meaning in a gravity field of 10^{-4} g) but only after all the essential experiments have been performed. The reason is that we have to design the docking operation before having seen the nucleus, therefore it is more risky than anything ever done before. The most important use of the mass spectrometer and x-ray fluorescence analyzer takes place between 1000 and 100 km from the nucleus. Beyond 1000 km, the phenomena are too much influenced by outside perturbations; within 100 km, the danger of dust covering is large.

I have alluded already to the origin of life: I would like to emphasize in Table 10 the three connected questions where the scientific returns seem most likely. First, the problem of the cometary depletions in H, C, N versus O. We have hints that these depletions have induced the conditions needed to reach the delicate balance of prebiotic chemistry. Second, we should check the nature of all HCNO molecules; I believe that we will certainly find amino acids as in carbonaceous chondrites. (Other scientists go further and believe we could find viruses!) Finally, the study of all isotopic ratios linked with all elementary depletions will tell us whether comets or carbonaceous chondrites or both were a late accretion veneer on the Earth and the source of the biosphere.

Finally, Table 11 summarizes the scientific objectives of a cometary mission. I have listed the science returns in front of the correlation with other fields--interstellar dust versus cometary grains--interstellar gas versus cometary gases--meteorites versus comets for the isotopic anomalies and the presolar origin of grains--building blocks of the solar system, exemplified by the cometary nucleus--final outcome of the nucleus,

Table 10.   ORIGIN OF LIFE

<u>SCIENCE OBJECTIVE</u>

HCNO abundances in comets

Nature of HCNO molecules
in comets

All isotopic ratios

<u>ASSUMPTIONS</u>

The cometary depletion in H, C
and N versus O may duplicate
the delicate balance to induce
prebiotic chemistry

Origin of amino acids

A late accretion veneer of comets
may be the source of the
terrestrial biosphere

<u>INSTRUMENTS NEEDED</u>

Neutral mass spectrometer
(range up to 250 AMU)

<u>SCIENCE RETURN</u>

HCNO, rare gas and other
isotopic ratios

Large molecule identifications

Search for amino acids, etc.

HOPE:

Checking Hoyle and Wickramasinghe's hypothesis: in comets,
amino acids and nucleotides have evolved into viruses or
protoviruses.   (Present terrestrial viruses are bacterial
parasites; however, in our ignorance of the early evolution
of bacteria, it seems likely that they were preceded by
simpler forms looking like viruses that were able to survive
without bacteria: the "protoviruses.")

Table 11.   SUMMARY OF POTENTIAL SCIENCE RETURNS

CORRELATION WITH:

Interstellar dust
(stellar evolution)

Interstellar gas
(chemistry of interstellar
clouds)

Meteorites
(origin of presolar nebula)

Accretion history of planets
(origin of solar system)

Meteors and meteor 'ds
(final outcome of interplanetary
matter)

All magnetized plasmas in
astrophysics

Physical chemistry

Origin of life

SCIENCE RETURN:

Nature, size distribution,
origin, evolution and age
of cometary grains

Molecular abundances in volatiles;
discovery of new molecules
undetected by radio-astronomy

Comparison with primitive
meteorites, isotopic anomalies
(in particular for H, C, N, O),
cosmochronology, mineralogy

Bulk nucleus: chemistry,
condensation, thermal history;
anisotropy, morphology,
differentiation; core, mantle,
crust "geology"

Cohesive strength of nucleus;
scale of heterogeneities (raisin-
bread model), "activity", decay,
snow sublimation, dust drag, size
distribution of lost fragments

Insight in plasma behavior through
interaction with solar wind;
ionization sources, motions, twists
and knots in tails, plasma waves

Photochemistry and charge-exchange
chemistry of cometary radicals:
parent molecules: ionization
mechanisms

Origin of depletions from HCNO
abundances; prebiotic chemistry
of HCNO molecules; source of
biosphere

into meteoroid and meteorites--cometary plasma, versus all plasmas from
the bow shock of planet Mercury to the magnetohydrodynamics of the
pulsars--the physical chemistry of the cometary coma to elucidate basic
mechanisms and phenomena--last but not least, the origin of life and the
possible source of the biosphere, through prebiotic chemistry.

I have just described a very heavy program, and it is filled with
unknowns and uncertainties. This is a sure sign that we have delineated
a virgin territory. We should not be afraid of all the uncertainties
but be encouraged by them. After all, if there were no unknowns, it
would not be worth doing.

Mission Tradeoffs

What is the trade-off if we choose to go to a less pristine comet?
This is an almost insoluble question. For instance, would we lose
something in the primitive nature of the accessible crust if we switched
from Comet Halley to Comet Encke? Certainly yes. How much? Nobody
knows. Comet Halley is more pristine and much brighter than Encke. As
such, it has had much more impact on the minds of men than any other
comet and for this reason, if we don't use its 1986 perihelion passage
for exploration, the people will wonder--too late-- why NASA isn't doing
something. But NASA knows that, and intends to do something. If, for
budgetary reasons beyond our control, we cannot do a rendezvous with
Comet Halley, we should at least do a Comet Halley flyby and go on to a
rendezvous with Comet Encke or some other short-period comet such as Tempel
2 or Giacobini-Zinner. This is an intriguing possibility that, I under-
stand, is going to be explored soon in more detail by JPL.

Conclusion

To remind you how Halley is historically linked with our western culture, I will finish on a well-known primitive image of the 1066 A.D. passage of Comet Halley found in the 11th century Tapestry of Bayeux, France (Figure 8). It happens that I have used this picture for the cover of the book that I have just published (1977). As you see, this figure is also shameless publicity for the book, which stems from IAU Colloquium No. 39 and is available only through The University of Toledo Bookstore. In my drawing here, there is a missing caption, written in Latin on the Bayeux Tapestry, that reads "isti mirant stellā," these (people) wonder because of the star. In the next scene, the tapestry depicts an astrologer telling King Harold of the bad omen brought by the comet. As everybody knows, King Harold was going to be killed a few months later at the Battle of Hastings. However, I prefer the scene I have used because it shows a pretty drawing of Comet Halley (with some imagination, you can identify its coma, its dust tail, and even its very narrow plasma tail with its knots and twists in the central part of the dust tail). Furthermore I prefer these faces, because they show exactly what astronomy is all about, wondering in front of an immense unknown universe. Mankind has not changed in nine centuries; there we were in 1066 A.D., there we will be again in 1986, wondering whether Comet Halley could throw some light on man's condition and origin.
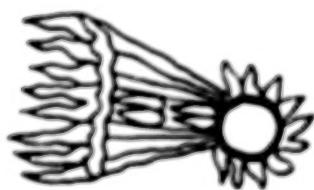
Fig. 8.   Sketch of Halley's Comet as shown on the Baveux tapestry.
Used as book cover illustration.

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COMET HALLEY AND HISTORY

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This meeting is being held at a most auspicious time, for we are just about to celebrate the four-hundredth anniversary of the birth of the scientific study of comets. Almost exactly four centuries ago, in November 1577, the Great Comet of that year burst over the skies of Europe (Fig. 1). Chief among those making observations of this comet was Tycho Brahe, at his observatory on the island of Hven. From a comparison of his own observations with those of other astronomers, notably Michael Maestlin in Würtemberg, Cornelius Gemma in Louvain and Thaddeus Hagecius in Prague, Tycho was able to demonstrate quite unequivocally that the comet was located at least four times farther away than the moon. As shown in Fig. 2, Tycho considered the comet to travel about the sun in a circular (or possibly slightly oval) path outside the orbits of Mercury and Venus, while the moon and the sun themselves orbited around the earth. Tycho's "System of the World" was a compromise between the Ptolemaic and the Copernican views, and while he was wrong about the details of the revolutions, particularly in the case of that of the comet, there is no doubt that he completely revolutionized thought on comets, which until then had held that comets were simply fiery exhalations in the earth's atmosphere. Terrestrial observations of countless comets since Tycho's time have considerably advanced our knowledge of these objects, of course, but on the occasion of this quatercentennial it seems appropriate that we should think in terms of another cometary revolution and make a definite commitment to launch a space mission to a comet.

More than a century was to pass after Tycho's revolution until the next significant contribution was made to cometary astronomy. Johannes Kepler made his brilliant discovery of the laws of planetary motion, but

Fig. 1. The Great Comet of 1577. The original shows a vivid
yellow comet, moon and stars in a light blue sky
(courtesy Istanbul University per O. Gingerich).
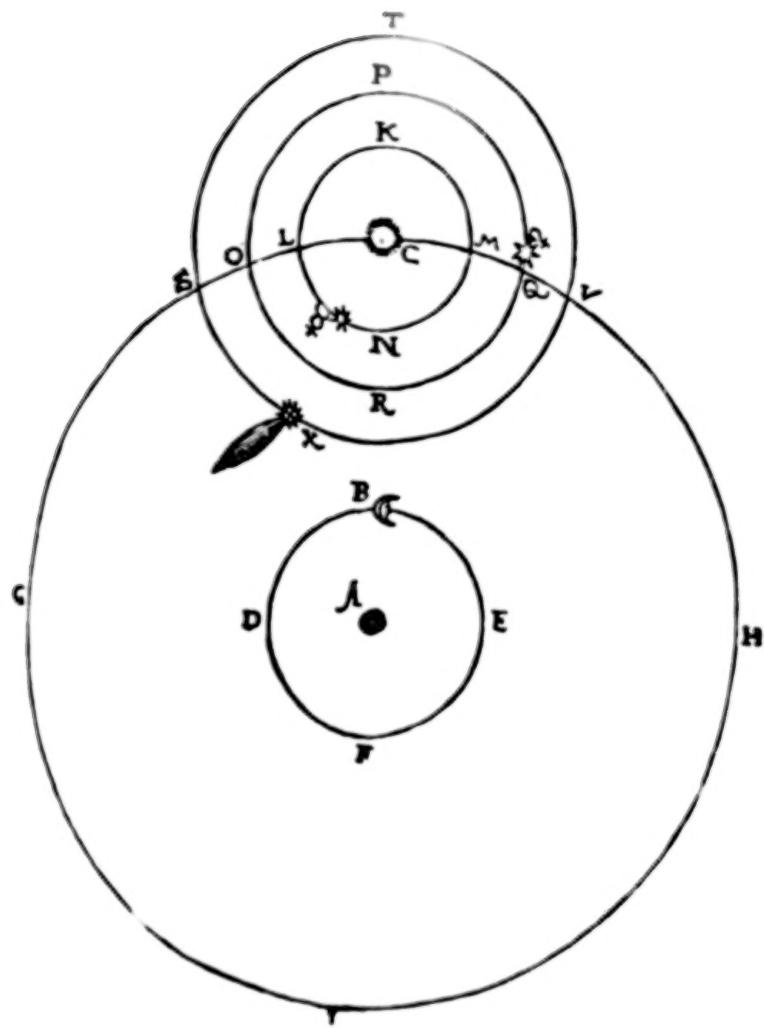
Fig. 2. Tycho's System of the World. The comet
of 1577 is shown orbiting the sun out-
side the orbits of Mercury and Venus,
while the moon and the sun are orbiting
the earth.

it never seems to have occurred to him that comets might be subject to
such laws. He steadfastly held to the neo-platonist view that the planets,
being eternal, have circular (or nearly circular) paths, whereas the
temporal comets must travel in straight lines. Other seventeenth-century
astronomers, notably Johannes Hevelius, began to suspect that comets moved
in elliptical or parabolic orbits, although Hevelius' adoption of the
latter was based on the idea that comets were projectiles thrown out by
Jupiter and Saturn, and the foci of the parabolas he calculated were not
situated at the sun. It was Georg Dörffel who was the first to realize,
in the case of the great comet of 1680, that the sun was at the focus of
the parabolic orbit, and soon afterwards Isaac Newton confirmed this by
showing that the motions of both planets and comets conform to the law
of gravitation.

As is well known, Edmond Halley then applied Newton's methods and
determined the orbits of 24 comets that had appeared between 1337 and
1698. In the course of his work, published in 1705, he made his famous
pronouncement concerning the identity of the comets of 1531, 1607 and
1682, suggesting that, with its period of $75\frac{1}{2}$ years, the comet should
return around the year 1758. It is perhaps not so well known that Halley
felt that the comets of 1532 and 1661 were also identical, and that the
great comet of 1680 was a return of one seen in the year 1106. Fig. 3
depicts the presumed orbits of the three comets, but we now know that
only the orbit with the $75\frac{1}{2}$-year period is correct.

Halley's 1758 prediction was refined by Alexis Clairaut, who, with
the assistance of Joseph Lalande and Madame Hortense Lepaute, worked
out step-by-step the effects of the gravitational attractions of Jupiter
and Saturn on the comet. It was a race against time, and they worked

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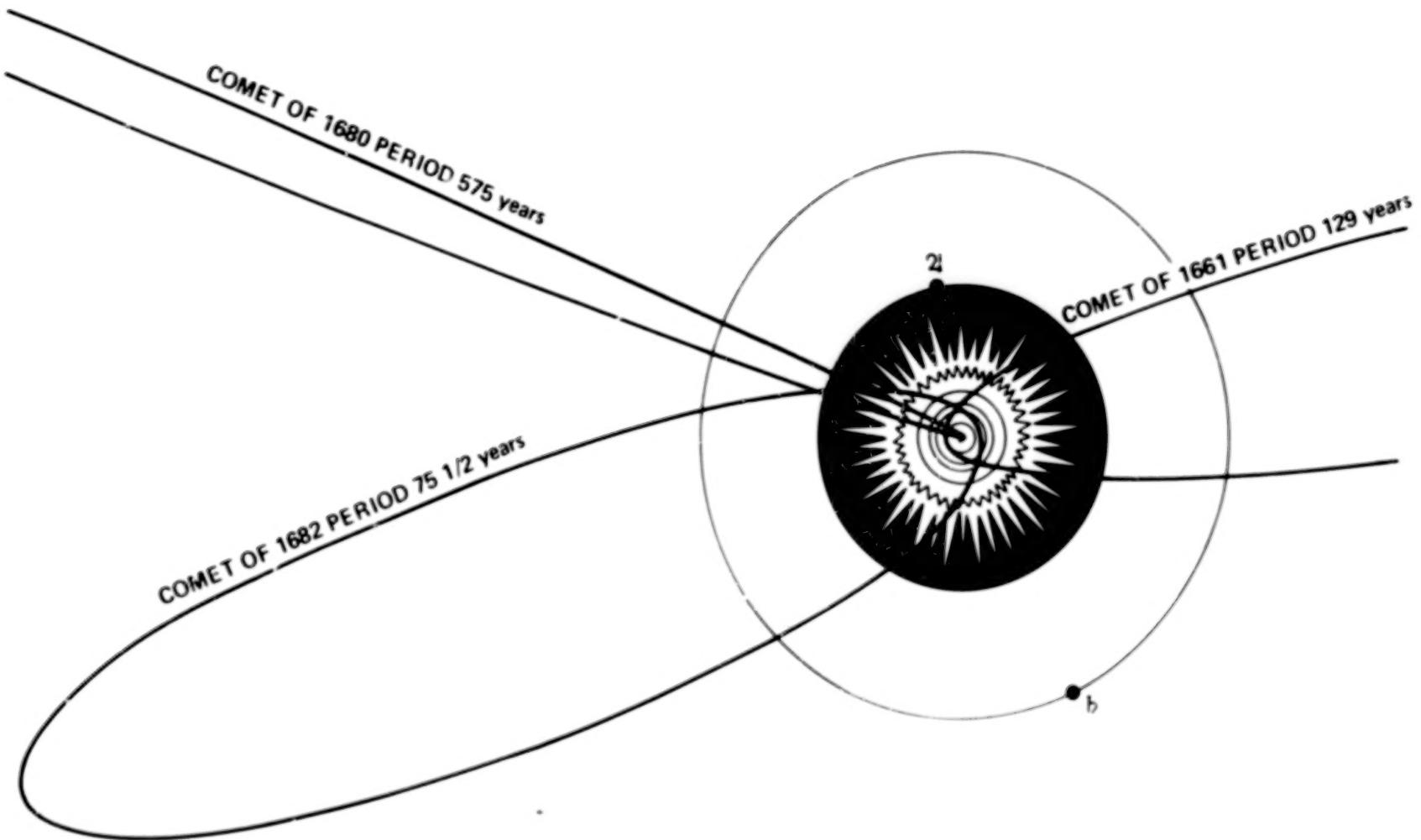
Fig. 3. Three of the comets supposed by Halley to be periodic.
Only the period of the comet of 1682 is correct.

from morning till night for six months. Clairaut was finally able to announce the result in November 1758. Fortunately, as Halley himself had indicated, the effect of the planets would be to delay the comet's return somewhat, and their predicted date for perihelion passage was 15 April 1759. The comet was recovered on 25 December 1758 by the farmer Johann Palitzsch near Dresden, almost a month before it was picked up by any of the professional astronomers who were making searches. Still ignorant of Palitzsch's prior claim, the first professional to find the comet was Charles Messier in Paris, but his announcement was also delayed owing to the pettiness of the observatory director Delisle. The observations indicated that the comet had returned just one month earlier than predicted, a remarkable achievement at that time.

Predictions for the comet's return in 1835 were due to Charles Damoiseau and Gustave de Pontécoulant in France and to Jacob Lehmann and Otto Rosenberger in Germany. The comet was recovered by Étienne Dumouchel in Rome, the observations indicating that Rosenberger's prediction was only four days too early. For the 1910 return, early predictions by de Pontecoulant and by Anders Ångström were refined by the British astronomers P. H. Cowell and A. C. D. Crommelin, and the recovery, first announced by Max Wolf in Heidelberg, again indicated that the best prediction was about three days too early.

Several astronomers, in particular J. R. Hind and P. A. E. Laugier in the mid-nineteenth century and Cowell and Crommelin early in the twentieth, attempted to trace the orbit of Halley's Comet back into the past, and the two last-named investigators succeeded in identifying observational records of the comet at every perihelion passage bar one back to 240 B.C. On re-examining their calculations in 1967 with a

high-speed computer H. F. Michielsen discovered that the computations
systematically required correction by about four days at each perihelion
passage, suggesting that the comet was being influenced by forces of a
regular, but nongravitational nature, such as those expected in the
case of Fred Whipple's cometary model. Michielsen was thus the first
to suggest that Halley's Comet will next be at perihelion on 9 February
1986, a result later confirmed by J. L. Brady and E. Carpenter by means
of the addition of a nongravitational term into the comet's equations
of motion. More recently, T. Kiang has refined the comet's perihelion
dates in the past with the help of ancient oriental observational records,
and using a more complete modeling of the nongravitational forces
D. K. Yeomans has made a definitive study of the comet's orbit since 837,
before which time the computations are rendered problematic because the
comet evidently passed only 4 million miles from the earth in that year.
Confirming the next perihelion date of 9 February 1986, Yeomans suggests
that there must still be an uncertainty of ± 0.25 day, and he gives
29 July 2061 as the date of the following perihelion passage.

Since time immemorial, comets have been regarded as portents of
disasters, and the discoveries of Tycho Brahe and Halley, not to mention
all the more recent research on the nature of comets, have done relatively
little to change this attitude. The past 2000 years have produced many
comets that are brighter than Halley's, but Halley's Comet seems to have
been responsible for more than its fair share of tragedies. In 12 B.C.
its appearance over Rome presaged the death of Agrippa, and its swordlike
appearance at its next return in A.D. 66 was regarded as a sign that
Jerusalem was shortly to be destroyed. It appeared in Europe in 451 at
the time of the battle of Châlons, when Attila the Hun was defeated by

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the Roman general Aetius -- a nice example of one man's meat being another's poison. The same was true in 1066 when, as the Bayeux tapestry depicts (Figure 4), the English were fearing for the safety of King Harold; on the other hand, the spectacular phenomenon appearing in the sky hardly bode ill for the invading Normans, and a contemporary Norman chronicle mentioned that the mysterious three-tailed star appeared simply because England wanted a new king, thereby giving William the Conqueror carte blanche. A French king got his come-uppance in 1223, however, and the appearance of Halley's Comet in that year was widely held as responsible. Perhaps the most famous ancient appearance of Halley's Comet is that of 1456, when the Turks were besieging Belgrade; Pope Calixtus III ordered prayers for deliverance from both the comet and the Turks, although the suggestion that he actually excommunicated the comet is certainly apocryphal. As the program for this meeting indicates, Halley's Comet inspired much public dread at its most recent return in 1910 (Fig. 5). Of course, there was on this occasion the unfortunate circumstance that the earth was actually to pass through the comet's tail, so one can perhaps understand why the ladies of Chicago stopped up their doors to keep out the deadly cyanogen gas. The entrepreneurs had a heyday selling "comet pills," and The New York Times shrugged off the episode in a delightfully poetic sub-headline: "Scarfed in a filmy bit of it, we'll whirl on in our dance through space, unharmed, and, most of us, unheeding."

The comet of 1680, such a source of inspiration to Isaac Newton, also played a role in the meandering thoughts of his not so illustrious successor to the Lucasian chair of mathematics at Cambridge, William Whiston. By indiscriminate application of the 575-year period suggested by Halley, Whiston attributed the Deluge to the comet -- though whether in 2344 B.C.

Fig. 4. Halley's Comet as recorded in 1066 on the Bayeux Tapestry.

Comet Halley   May 6.9, 1910
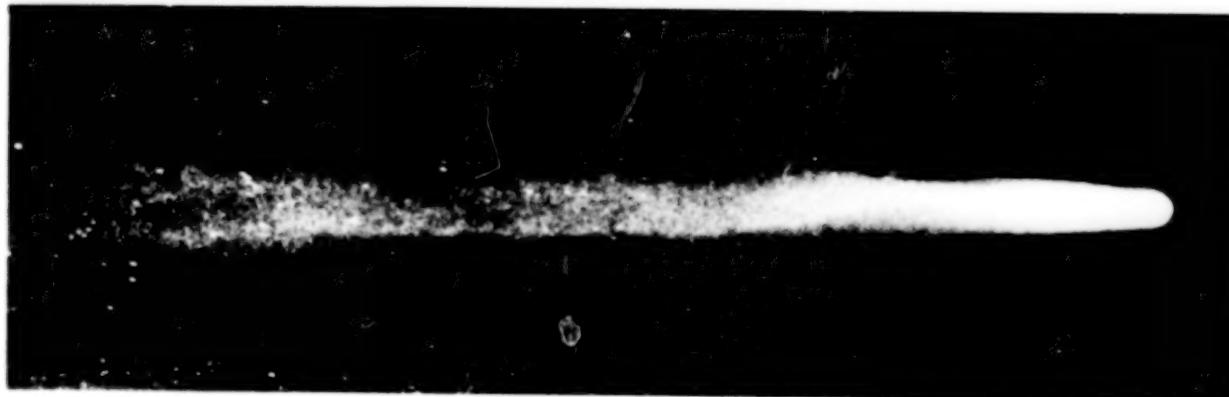
Comet Halley   May 7.9, 1910

Fig. 5. Halley's Comet as observed on 6 and 7 May 1910 at the Mt. Wilson Observatory.

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or in 2919 B.C. is not completely clear; and he suggested that the comet's next return in A.D. 2255 will signify the end of the world! In 1680, the feeble of mind were terrified by the report that a hen laid a "wonder egg" marked with a comet. The Paris Academy later corrected the story by noting that the hen had never in fact laid an egg before, that the event caused the hen to cackle extraordinarily loudly, that the egg was uncommonly large, and that it was marked, not with a comet, but with several stars (Fig. 6).

In contrast to most of its brethren, the comet of 1811 seems generally to have been regarded in a beneficial manner. It was presumed responsible for the excellent port and claret vintages of that year, and Napoleon considered it a good omen for his march to Moscow. Napoleon always felt that comets were beneficial to him, for one had been present at his birth in 1769. As it turned out, the comet of 1811 did not do him much good. Donati's Comet of 1858 (Fig. 7) also apparently yielded an excellent claret, but Lord Malmesbury wrote in his diary: "Everyone now believes in war."

The possibility that the earth would collide with a comet always excites the public imagination. As expected, the earth suffered no ill effects when it passed through the tail of Halley's Comet in 1910, but what about a collision with a comet's head? A paper announced by Lalande in 1773 set Paris into a terrible panic. Although concluding that the possibility was extremely remote, the paper discussed how planetary perturbations could deflect a comet enough to make a collision occur. As it happened, the paper was not given at its appointed time, and -- to Lalande's extreme embarrassment -- a vivid public imagination soon convinced the populace that the earth was in imminent danger of

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Wunder-Ey.

Welches den ... Decembris dieses mit GOtt zu Endlauffenden 1680. Heil-Jahrs zu Rom / von einer Henne mit grossen Geschrey ist geleget / und von hoher glaubwürdiger Hand solcher Gestalt in den Entwurff und Abriß gebracht worden.
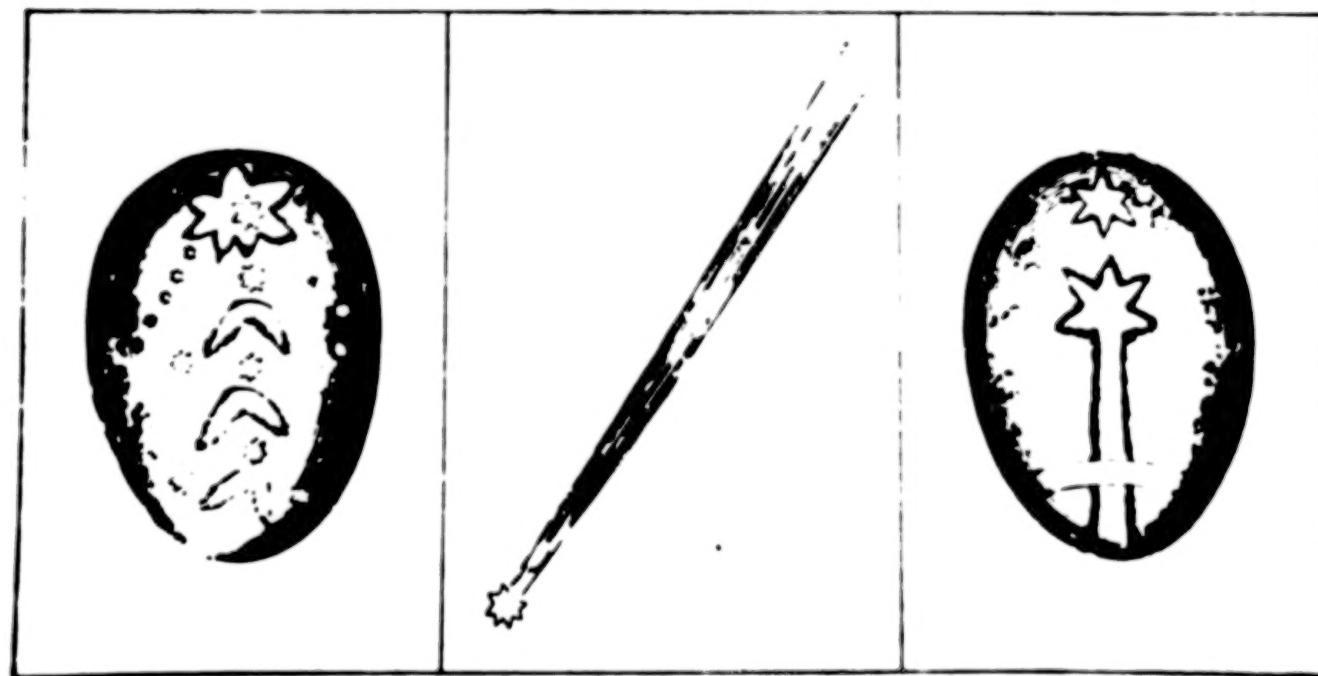

Fig. 6.   The "wonder egg," allegedly laid with the comet of 1680 marked on it.

Fig. 7. Evidently Donati's Comet in October 1858.

destruction. Biela's Comet has often been a source of distress: when Wilhelm Olbers pointed out that in 1832 the comet would pass within 20,000 miles of the earth's orbit, his qualifying remark that the earth would not reach that part of its orbit for another month went virtually unnoticed; and the unusually warm weather in Atlanta, Georgia, in November 1872 led a later generation to believe that the comet was bringing about the end of the world. Perhaps the most famous panic of this type was occasioned in 1857 (Fig. 8) by a pamphlet entitled "Will the Great Comet Now Rapidly Approaching Strike the Earth?" The event under consideration was the presumed return of the comet of 1264 and 1556 -- although as it turned out no comet came at all, and the identity of the 1264 and 1556 comets is highly questionable.

But the present age is certainly no more enlightened in this respect, and the sensationalist press produced headlines like "Comet May Kill Millions" when the notorious Comet Kohoutek was approaching its perihelion passage at the end of 1973. The article goes on: "If the enormous comet should land in any of the world's oceans, tidal waves as high as 100 feet would sweep over coastal cities as far as 2000 miles away." It admits that the "dreaded comet ... may not come close enough -- but it may" and quotes a Dr. Bernard Hostetter of the Smithsonian Astrophysical Observatory as saying "we have absolutely no way to know." There is not and never was a Dr. Bernard Hostetter at the Smithsonian Astrophysical Observatory, and if the newspaper had chosen to check its facts with any responsible person on the staff it could easily have learned that Comet Kohoutek would miss us by a clear 75 million miles.

While much of the other press coverage of Comet Kohoutek was decidedly unsatisfactory, most of it was more responsible than the above. After the

Fig. 8. Cartoon inspired by the expected collision of a comet with the earth in 1857.

initial build-up, the press somehow felt obliged to follow through. One can, I suppose, excuse such headlines as "The Star-Spangled Ripoff" and "Kohoutek's Dim Display Makes it Astronomy's Edsel, but Scientists Enjoyed Ride," as well as some of the cartoons that appeared (Fig. 9). Even if Comet Kohoutek had been as bright as some of the early predictions suggested, those hoping to see it streaking across a light-polluted sky would have been disappointed. The well-publicized Comet Ikeya-Seki of 1965 was also a dud as far as the public in the northern part of the U.S. was concerned, yet the two most spectacular comets observable from north temperate latitudes in recent years, Bennett in 1970 and West in 1976, at their best in the morning sky, were virtually ignored by the press.

Unfortunately, in 1985-6, Halley's Comet is expected to be even fainter than its 1974 predecessor, Comet Kohoutek. If one wants to have a good view of Halley's Comet, he should plan a trip to the southern hemisphere in March or April 1986, when it should be a moderately impressive object in the early morning hours. It is as well that we do not raise too high the hopes of those who want to see this celestial visitor about which they have heard so much. On the other hand, it is still possible that the public can receive vicarious pleasure in that a space probe will be out there adding to our understanding of this mysterious body at an opportunity that presents itself once a lifetime. To the man in the street, the solar system consists of Mars, the rings of Saturn and Halley's Comet. Viking missions have taught us a lot about Mars, and probes are on their way to the vicinity of Saturn. If we omit Halley's Comet from all consideration for space exploration, it seems to me that the public is going to want to know why.

"Well, that's the last of the Christmas lights, pop. Frankly, I think we overdid it this year."

Fig. 9. Cartoon inspired by the disappointing display of Comet Kohoutek in 1974 (reprinted by permission of the Chicago Tribune--New York News Syndicate, Inc.).

ION PROPULSION AND COMET HALLEY RENDEZVOUS

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I couldn't help thinking, as Professor Delsemme was talking, of an analogy with Professor Delsemme as Captain Ahab and this great white ghost in the sky as some "Moby Comet." And the mission I propose uses an instrumented probe as your harpoon.

Ion drive, an advanced propulsion system, will provide the ship, taking us out to the comet and allowing our "harpoon" to sample the comet. Some day perhaps we'll bring the sample back and put it into a museum, or a zoo, which-ever may be appropriate.

In speaking about a mission to a comet, specifically a Comet Rendezvous, we are talking about a significant energy problem in terms of what it takes to get there. The basic problem follows from an understanding of the cometary orbits that were shown by Professor Whipple earlier in the day. They were generally quite elliptic, or "egg-shaped", and most of them are highly inclined to the ecliptic plane. Thus to intercept and match the cometary paths we must change both the shape and the spatial orientation from a flat circular orbit to an inclined elliptical one. This maneuver requires more energy than is generally available from our conventional rockets. You see in Figure 1. an estimate of the launch mass capabilities of several Shuttle and Inertial Upper Stage combinations. The launch energy parameter C_j is on the abscissa. This is a measure of how much energy is put into the transplanetary trajectory.

If we overlay this capability with the requirements of a number of space missions (Figure 2) -- and I apologize that the chart gets a bit busy -- we can see that missions lying below the curves are within our general capability.

I have encircled general mission regions indicating the energy classes. Basically, this shows that conventional chemical systems are unable to capture comet rendezvous missions even if we projected four stage versions of the IUS. Obviously we need some advanced propulsion capability to brighten the bleak prospects for comet rendezvous.
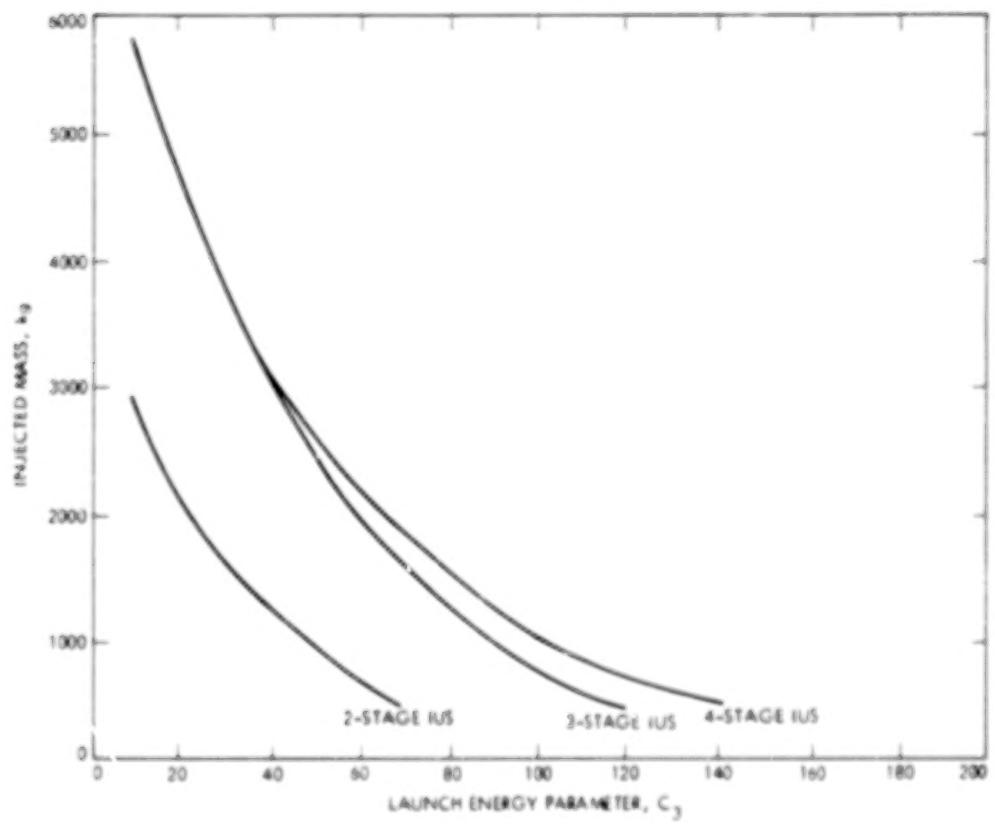
Fig. 1. Shuttle/IUS capabilities.
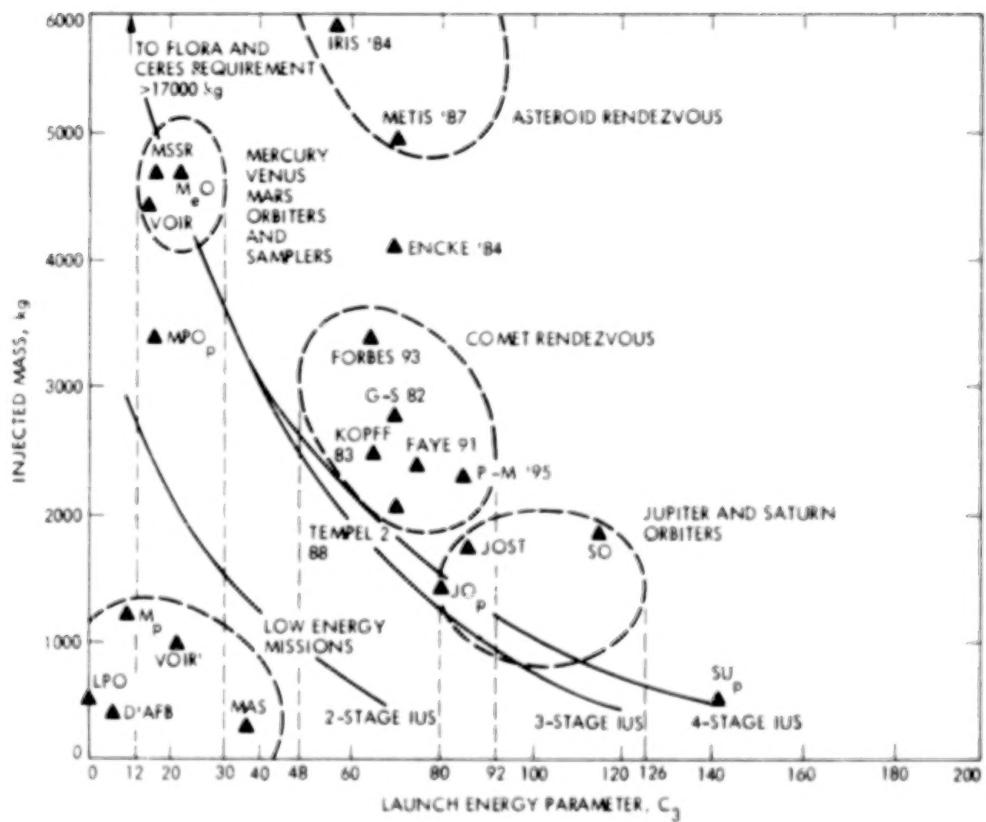
Fig. 2. General requirements for selected ballistic missions.

In the last several years NASA has funded the development of ion propulsion. This system uses ion rocket engines that have a fuel efficiency, or a "miles-per-gallon" improvement on the order of 10 times better than chemical rockets. This says that you can deliver over four times the amount of total impulse than you can with a chemical system while using less than half the fuel.

This allows us to talk about making impulse changes equivalent to that required to achieve a rendezvous with Comet Halley.

Cometary rendezvous missions are not the only customers for ion propulsion. This flight system has a number of applications in the planetary regime. Missions such as Mercury orbiters, Mars sample returns, and Saturn orbiters are included along with bringing back the museum piece for Professor Delsemme. It also has some applications in Earth orbit. I will not dwell on those today, but I would like to have you recognize that this system is something that carries a broader interest than applications in comet missions.

Let's talk about some of the characteristics of this system. I have already alluded to the high fuel efficiency; a factor of 10 improvement. Ion propulsion uses an inert fuel, liquid mercury. Liquid mercury looks nothing like a comet so you do not mistake things you might see from your engine for things you might see in a comet.

The acceleration is very low. You get only about 0.002 pound of thrust per engine; but the system will be operated for significantly long periods of time. Two or three years of continuous propulsion is something that appears to be well within the capabilities of the technology. The integral will provide very respectable vehicle velocities.

One of the reasons the engine can last so long is that it has no moving parts. The only real wear-out mechanism that we worry about is the erosion of the accelerator grid caused by the particles as they pass through and are exhausted from the engine.

Ion engines provide a modular approach to spacecraft design. Several engines can be clustered, each with its individual support equipment. Each engine unit may be considered as a module. This allows a lot of flexibility to vary the number of thrust units to match the mission requirements. Fewer engines are required for some applications while more are necessary for others.

Further examining its operational characteristics, we recognize that an electric system like this generates electric and magnetic fields. We have to deal with electric and magnetic interaction with the rest of the spacecraft. The charged exhaust particles lead us to concerns about deposition on surfaces and attenuations if we communicate through the exhaust plume. I'll come back to this later.

Now, I would like to describe the physical characteristics of an ion propelled spacecraft. Figure 3 identifies the basic parts of the vehicle. It is comprised of the thrust module, an interface unit and the large solar arrays that collect sunlight and turn it into electricity for actually operating the engines. Above the dotted line is the scientific spacecraft or the payload. It consists of a mission module that carries all the command and control equipment and a science package.

Figure 4 shows the design developed for a Halley rendezvous mission. This artist's rendition displays the thrust subsystem with the ion engines to the right. On the sides are the large, solar arrays with reflectors to collect the sunlight and focus it on the solar cells at the bottom of the trough. The technique of light concentration through use of the reflectors essentially fools the solar cells into thinking they are closer to the sun than they really are, and this mitigates the magnitude of the power loss experienced as we go away from the sun. Thus, thrust performance stays at a relatively high level. Higher thrust leads to larger payloads and shorter flight times.
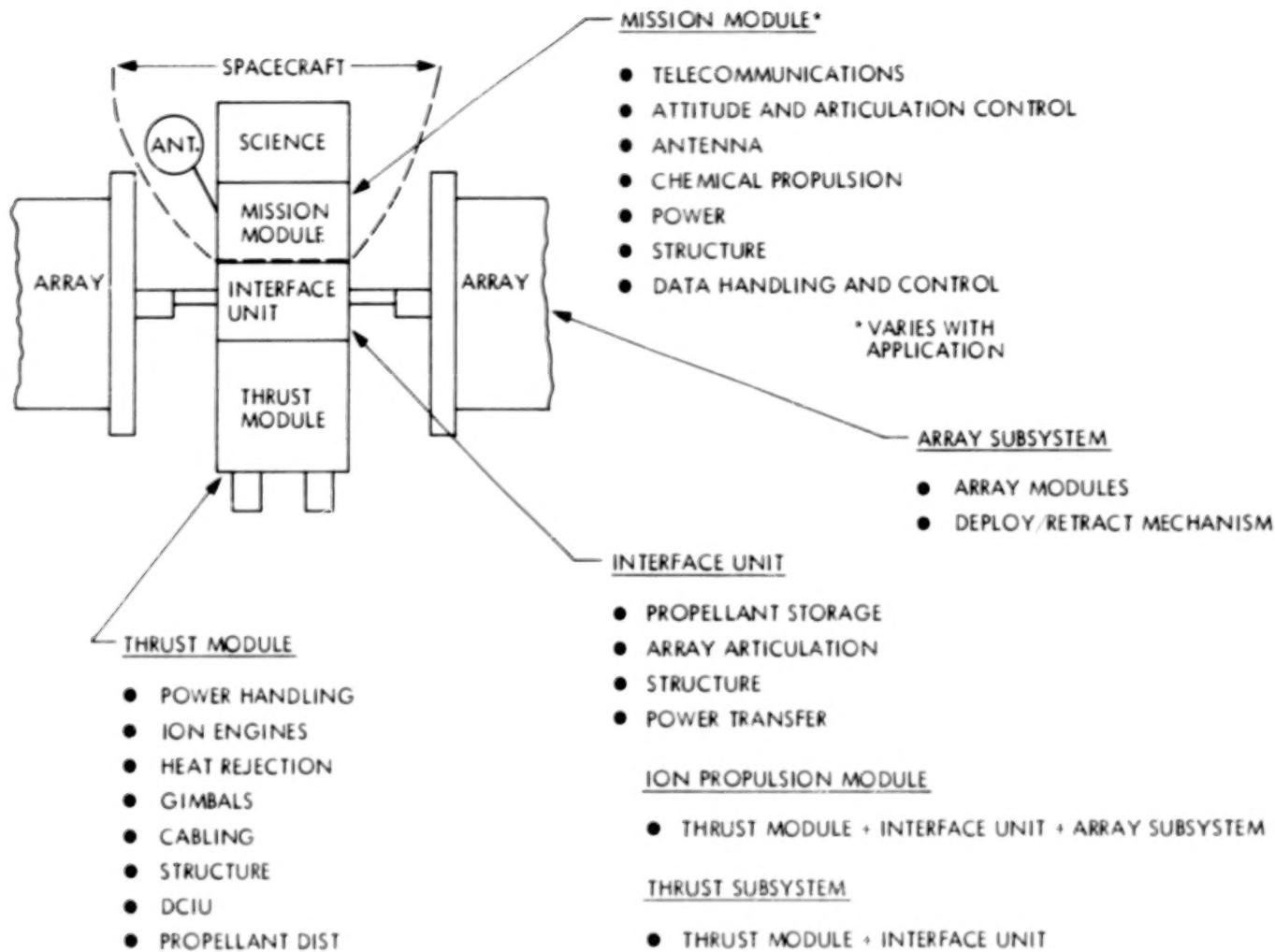
Fig. 3. Ion drive vehicle definitions.

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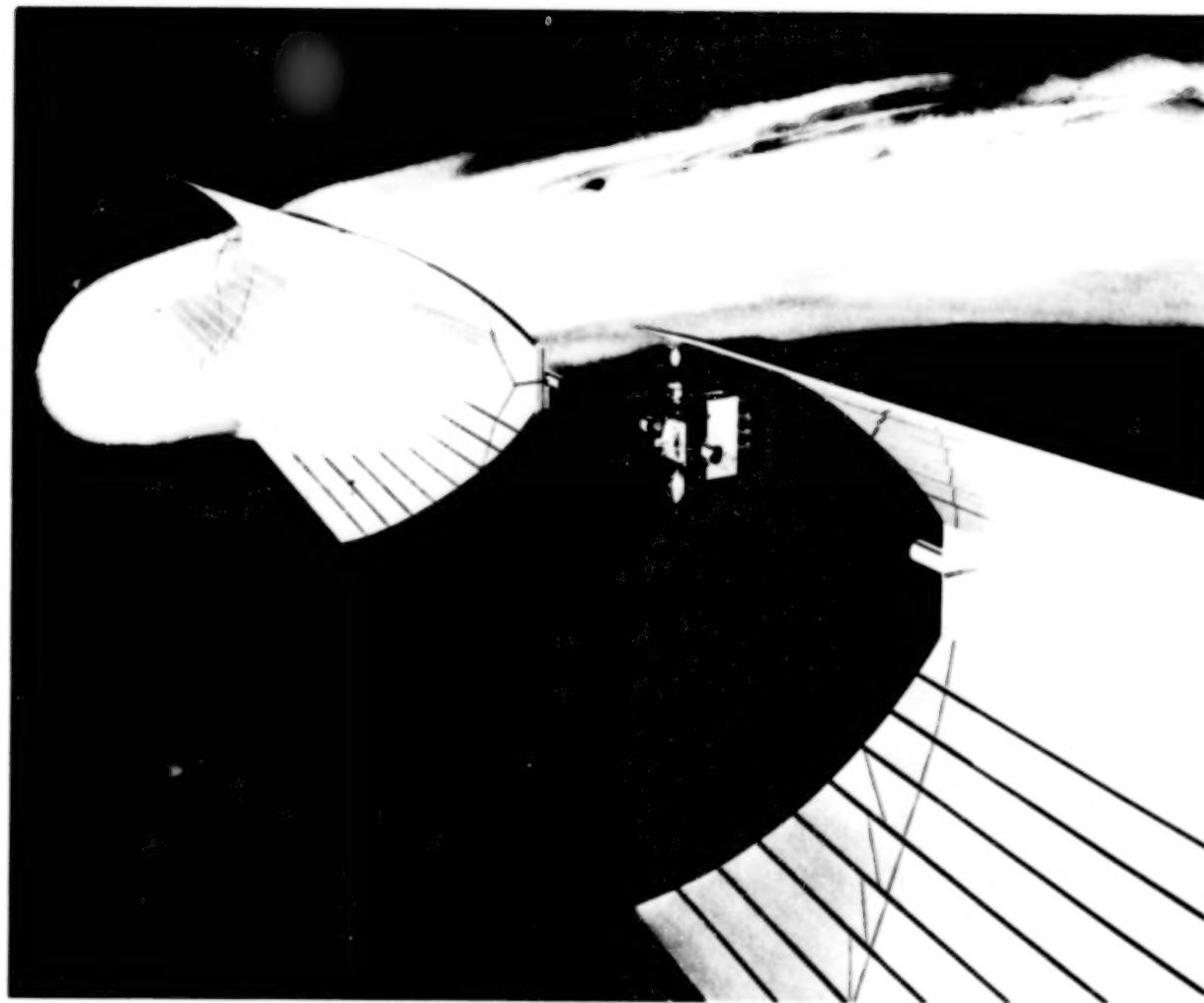
Fig. 4. Artist's conception of ion drive vehicle required for a rendezvous with Halley's comet.

The dimensions of the vehicle from "wing tip to wing tip" are something on the order of 450 to 490 feet. The array wings are about 12 feet wide, so you can see this is not a small machine. Each engine is 15 inches in diameter. You may think that 450 feet is fairly long (it is about a football field and a half from one wing tip to the other). However, on the scale of some systems that have been considered for the Halley rendezvous, the ion drive vehicle is relatively small. The solar sail, which was considered as an alternative technique for accomplishing a Halley Rendezvous mission, was nearly nine miles from wing tip to wing tip.

A better understanding of the ion propulsion technique is gained from looking at the engine cutaway shown in Figure 5. The ion engine is deceptively simple in its operation. It looks much like a coffee can about 15 inches in diameter and about 10 inches deep. The fuel, in liquid form, is brought in through a couple of heaters or vaporizers that transform the liquid mercury fuel to a vapor and distribute it through this manifold. At the base of the engine is an electron emitter or cathode. Electrons flow from the cathode to the anode out around the circumference. The electrons pass through the mercury vapor and cause ionizing collisions. Once charged, the mercury ions are forced by magnetic and electric fields toward the two accelerating screens over the exhaust end of the engine. A high electric field is placed between these two separated screens so that as the ions drift into it they are accelerated to a very high velocity and exhausted at speeds ranging from 50,000 to 75,000 miles per hour. The achievement of very high exhaust speeds at relatively small expenditures of energy leads to the benefit of high fuel efficiency. The engines thus offer a tremendous advantage in doing missions that we ordinarily refer to as "high energy requirers". They allow achievement of these missions for relatively small amounts of "fuel". Figure 6 shows a photograph of one
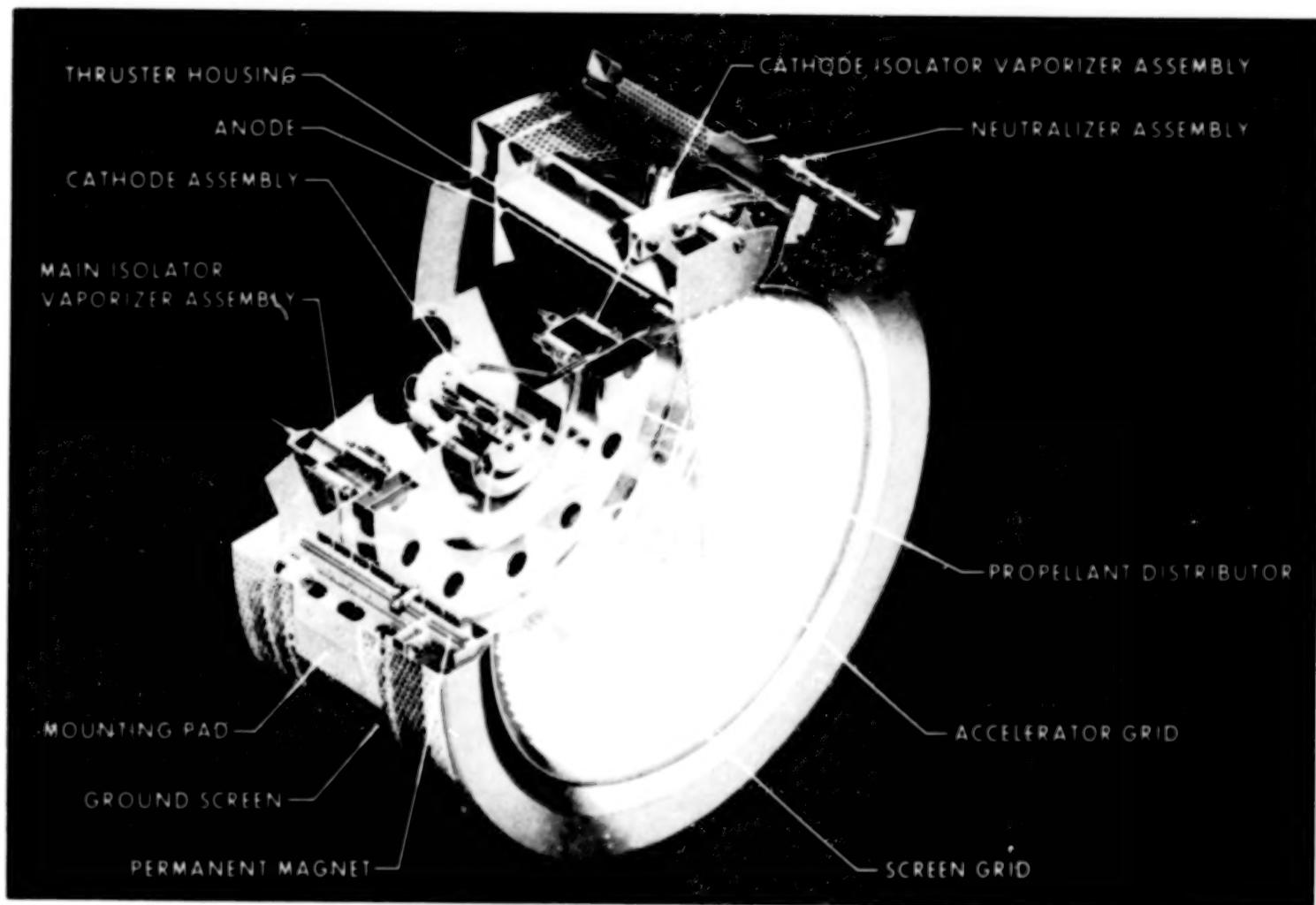
Fig. 5. Model of ion engine.
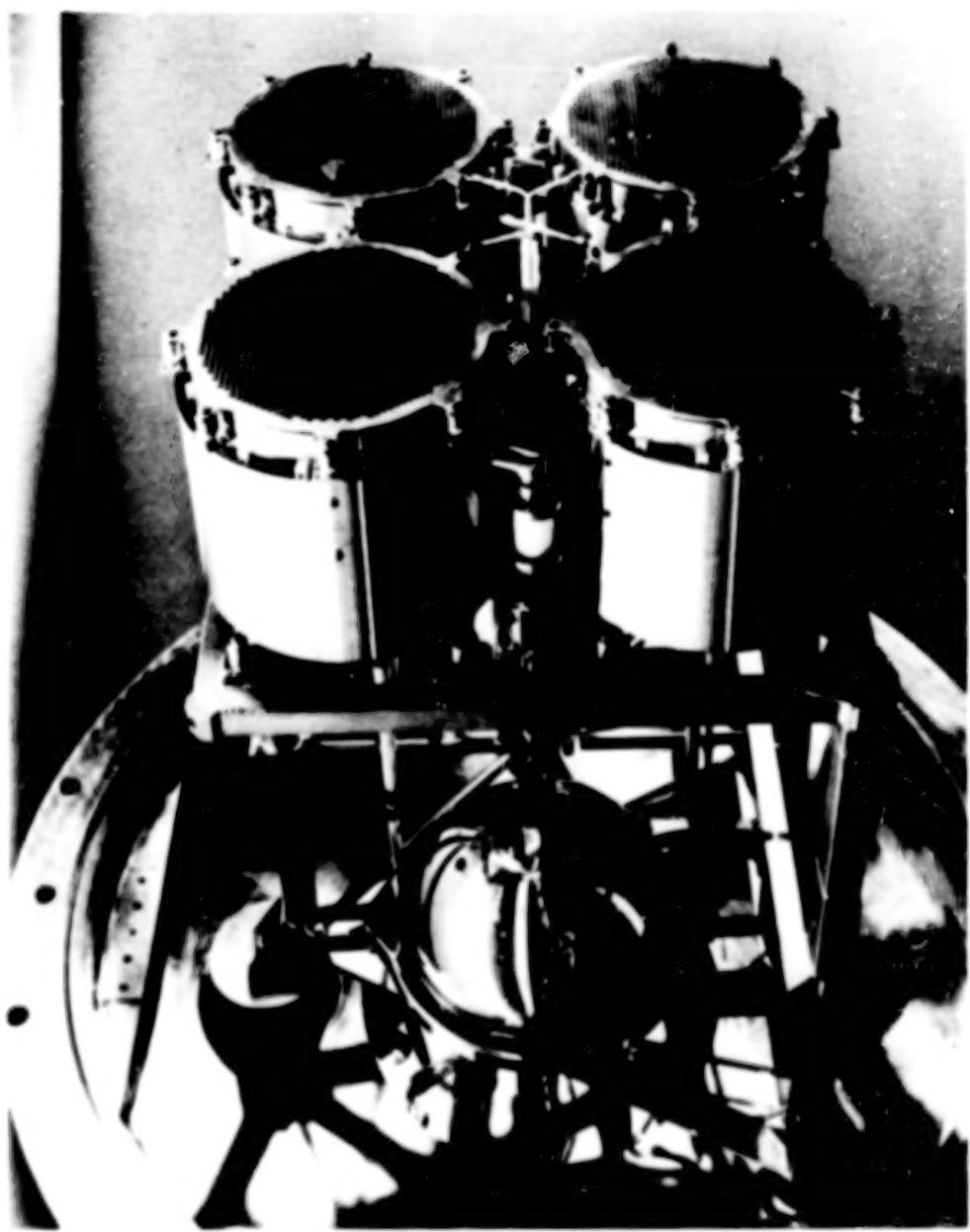
Fig. 6.   Photograph   an ion engine.

of the engines. These engines have been tested both on Earth and in space and are still undergoing tests at Lewis Research Center and its contractors.

The modular nature of the thrust subsystem is shown by the scale model in Figure 7. This model has thrust units that combine two of these engines in each module with the electric power processing equipment in two racks at the end opposite the engines. The plates on the side are radiators which take away the excess heat that can't be used in the power conversion process. The components, put together in this fashion, become bimodular thrust units that can be standardized and stacked tinker-toy fashion to form a thrust subsystem for the ion drive rendezvous.

In the interface unit, just forward of the thrust modules, a propellant tank and two roots for the connection of the solar arrays are housed. The interface unit also provides the hard points for mounting the spacecraft.

Figure 8 depicts, in a series of scenes showing six different events, the ion drive deployment from the shuttle. Basically, we start at the bottom left with the ion drive stowed in the shuttle atop its twin-stage, solid, rocket booster. This stack is then erected in the shuttle bay and separated. The shuttle backs away to a safe distance and as the 3rd scene shows, the solid rocket booster is ignited and drives the ion rocket to a positive escape energy relative to Earth.

The fourth event shows burnout of the solid and separation of the ion system. Event 5 shows the beginning of the deployment of the solar arrays while the final scene at the lower right shows the partially deployed arrays that signal the beginning of the ion thrust phase.

Let's now discuss science acquisition options. We understand your concerns about operating with a system that has large electric and magnetic fields. There are several modes for science acquisition in such an environment. First, we have no difficulty in shutting the thrusters off, and in fact, the design

Fig. 7. Model showing possible modular construction of an ion propulsion system.
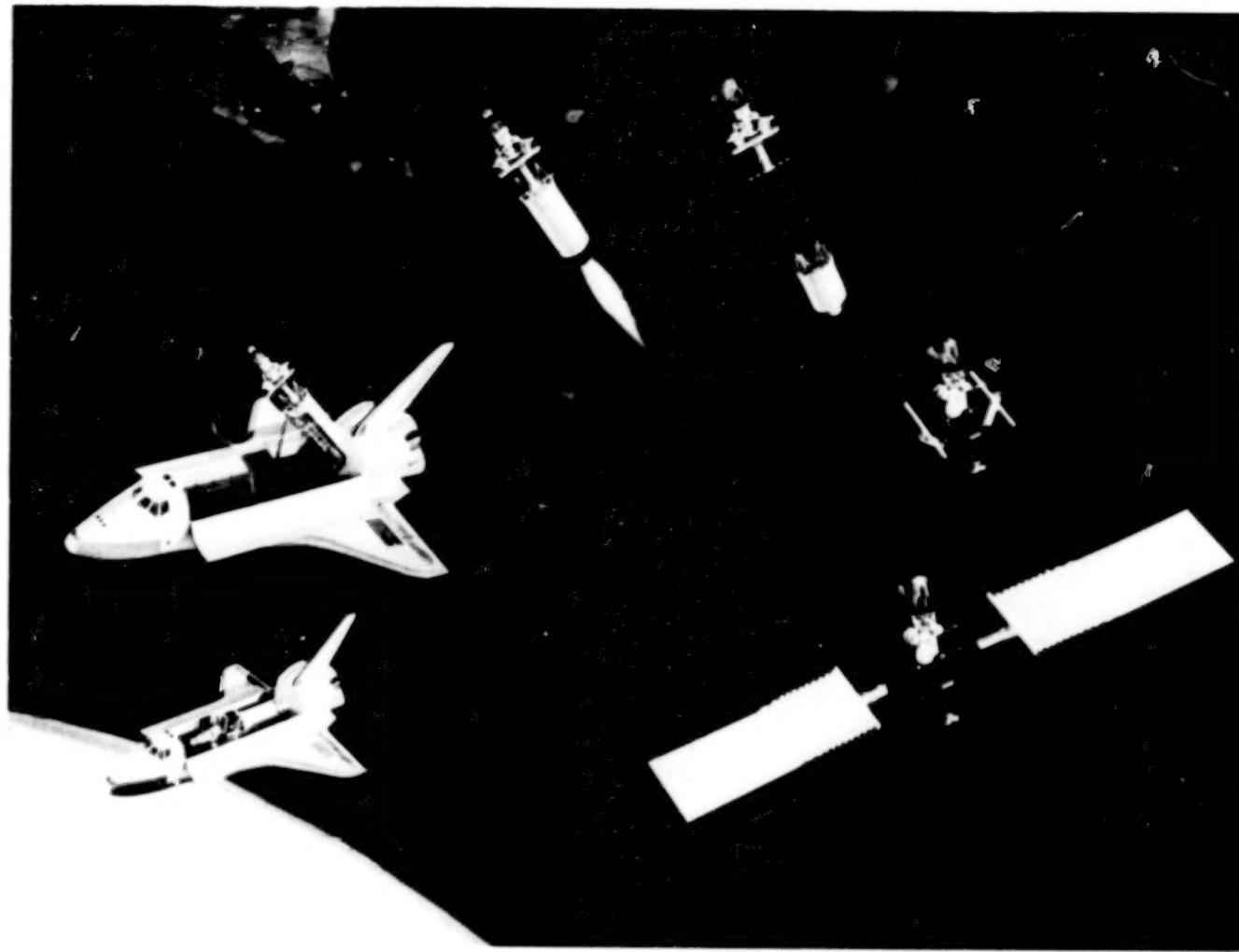
Fig. 6. Ion propulsion system deployment from the Shuttle/IUS.

of the Halley comet mission calls for exploration strategies where during most of our time in the vicinity of the comet, the engines are shut down and in a very quiet "coast" mode for taking the science data. Another option is to keep one of the engine neutralizers operating. This achieves active control of the spacecraft potential by providing a controlled source of electrons to balance charge build-up.

In a third option, we could continue to operate the engines and take data while both thrusters and neutralizers are operating. There are several ways to handle the problems caused in that mode. We can use clever positioning of the instruments, such as on booms, or we can shield the instruments.

We have also looked at the difficulties or concerns that might be seen in handling a mercury propellant, both in loading it and launching. A number of "worst-case" situations such as reentry of the entire mercury tank after an explosion during launch have been studied. These studies found that the effect on the Earth's environment is equivalent to a temperature change resulting from a trip of 300 miles; you deplete the ozone layer in a very, very limited vicinity for a short period of time.

In talking about missions to comets with ion drive there are several but a limited number of options for targets. I will discuss two today - the Halley Rendezvous and the Encke Rendezvous. Both have received considerable interest from the Science Working Group.

Figure 9 is a picture of the trajectory to achieve rendezvous with Halley's comet. The orbit of Earth is a dark circle. The launch would occur somewhere around June, 1982. The spacecraft goes out, away from the Earth, and begins to slow down much like a rock thrown up in the gravitational field. Then it "hangs a left", or makes a big "U turn" and begins to thrust back toward the sun. The orbit of Halley's comet is the dashed curve. The rendezvous occurs
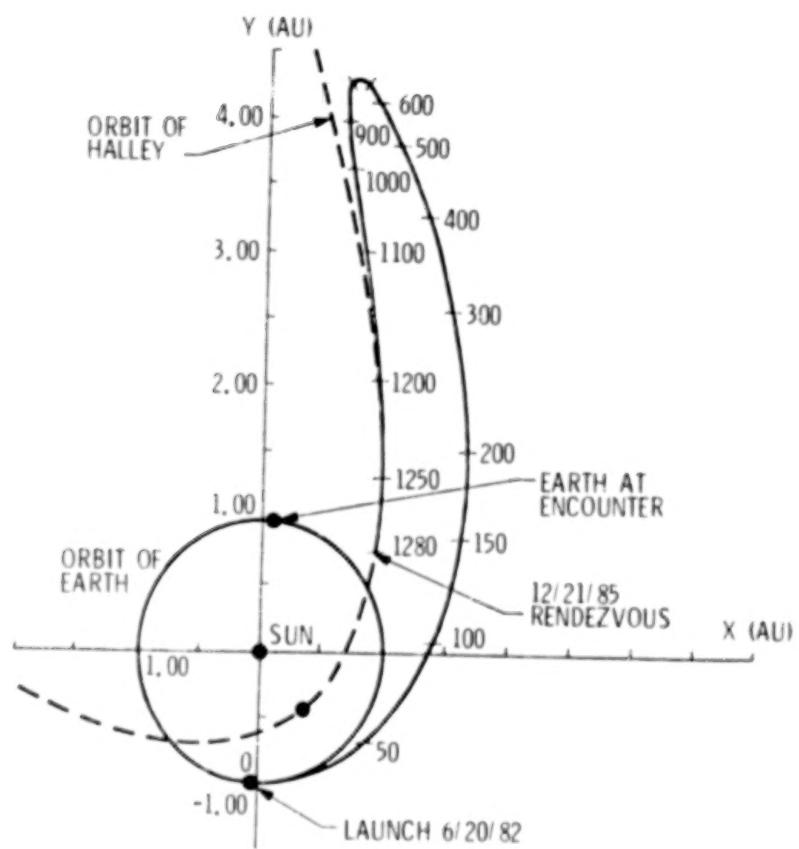
Fig. 9.   Ion drive trajectory to attain a rendezvous
with Halley's comet.

when the comet overtakes the spacecraft, just before Christmas, 1985. It will make an interesting Christmas star as seen from the spacecraft.

The other alternative target is comet Encke. Figure 10 shows the trajectory for Encke's 1987 apparition. The launch would occur in March, 1985. The spacecraft would arrive 700 or 800 days later in May, 1987, some 50 to 60 days before perihelion. During this particular apparition of Encke, the Earth is across the solar system from the comet. This situation is not particularly attractive for ground based optical observations of comet Encke, but we see no real difficulties in communication with the spacecraft during the rendezvous.

One thing about the Encke mission that I think is significant is how close it passes the sun during its perihelion, about 0.34 astronomical units. That is going to be a very hot thermal environment, and it is going to take some clever approaches on the part of engineers in order to solve the thermal problem if this mission receives serious consideration.

In summary, I've introduced ion drive, discussed its characteristics and operation, and briefly overviewed its potentially wide spectrum of applications. Its modular nature and high fuel efficiency while operating from electricity generated by collecting sunlight make it an ideal adjunct to the Shuttle Transportation System. I specifically addressed its unique potential for achieving comet rendezvous and used the examples of Halley's comet and Encke as prime mission candidates. I hope from this brief introduction I've been able to transmit something of the excitement I think is inherent in the combination of an exotic new propulsion technique, ion drive, with a mission to investigate Halley's and other comets.
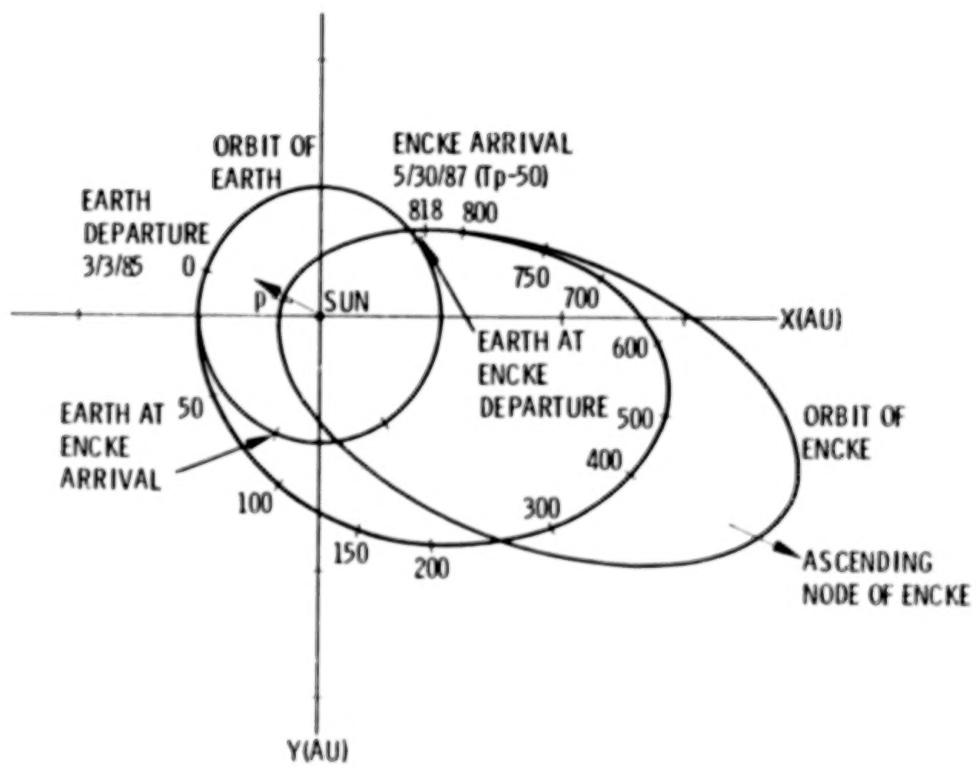
Fig. 10. Encke rendezvous (1987) trajectory.

SUMMARY OF PANEL DISCUSSION

Edited by C. R. O'Dell

PARTICIPANTS

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George B. Field, Center for Astrophysics
Daniel H. Herman, NASA Headquarters
Brian Marsden, Center for Astrophysics
David Morrison, NASA Headquarters
C. R. O'Dell, Marshall Space Flight Center (Chairman)
Fred Whipple, Center for Astrophysics
Thomas A. Young, NASA Headquarters

The initial and most animated discussion was on the question of what are the actual plans of NASA for future comet missions. The NASA Headquarters respondents were unable to give clear answers on this topic due to the fact that the plans had been submitted as part of the NASA budget to the Office of Management and Budget; as such they were confidential until the President submits his budget to the Congress in January. However, it was obvious that something is in the offing, as NASA has now completed its technology assessments of comet missions and feels ready to proceed. Exactly what missions(s) (flyby or rendezvous) and what comet(s) was left open. Comet Halley is attractive from a science and historic perspective but a rendezvous mission would involve an impractical early launch time and early year funding.

By now there have been numerous workshops, investigative committees, and studies of comet missions. There seems to be no doubt that such missions are scientifically valuable and are feasible. The group assembled for this meeting is probably the strongest ever; it is large in size and NASA should take note. It is time to get something started. This opinion was shared by all present.

The comet-research scientists clearly want a program office for comets within the Office of Space Science structure at NASA Headquarters. They feel that comets have somewhat been the planetary stepchild and that only by having the recognized position of an office would this situation be changed. The Headquarters answers did not hold out any real promise that this would happen.

Professor Whipple emphasized the importance of a rendezvous mission or very slow flyby for the study of the nucleus itself. Angular

resolutions required are $\leq$100 m for the general structure and the order of 1 m divided by the density for looking at the constituents, such as cometesimals, which formed the nucleus.

The final discussion was about the importance of Comet Halley. It is the most famous of the known comets and has been observed for over 2000 years at essentially every return. It is scientifically important and is well known to the public. The supportive lay public simply cannot understand the timidity of NASA in failing to establish a clear scientific mission around Comet Halley. The fact that this will not be a favorable apparition can be handled and the public will support this type of space mission. Lay groups have affected government decisions before; perhaps it can be done again.

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Summarizing Comments

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I am not really going to attempt to summarize all the excellent presentations that have been given today. I simply would like to elaborate a little bit on several themes which have run through many of these discussions, including those of the panel a few minutes ago.

(1) On the Origin of the Solar System.

Many of the speakers, and particularly Armand Delsemme, have explained at some length the intimate relationship between the early history of the solar system, the origin of the solar system, the origin of the Sun, and what we might expect to learn from missions to comets. Everyone recognizes that understanding the origin of the solar system is a most fundamental scientific problem. Whipple and Chang referred to the idea that even the origin of life may be associated with comets. If so, the study of comets becomes a search for our "roots."

It may seem a bit odd that in spite of the rather overwhelming case that has been made for the fundamental significance of these studies, at least in the past we have not seen our scientific colleagues or NASA officials standing on their feet shouting, "On to the nucleus!" I think it is of some importance to understand why they haven't. I think the answer bears on a fundamental problem of our field of science: there is a very serious gap between theory, experiment, and observation. There is not at present any genuinely respectable theory which leads to clean predictions concerning what these missions should find. This problem is not unknown to other fields of science, but its importance varies considerably from one scientific field to another.

We might contrast our situation with the circumstances of the early 1930's when Pauli predicted the existence of the neutrino, the experimental detection of which was far beyond the abilities of the most sensitive aparatus of that time. The idea of trying to measure a nuclear reaction with a cross section of 10^{-44} cm^2 was just way beyond anything anyone thought possible. Nevertheless,

the identification of this particle remained a major goal for experimental physicists for the next 15 years, and this goal was achieved. In a similar way the prediction of the existence of the anti-proton was sufficient to provide the funding for the building of the great bevatron accelerator at the Lawrence Berkeley Laboratory.

So we see a contrast: in both cases difficult and expensive efforts were required. In the case of physics, the community support was there. Even though Ken Atkins has told us how we might rendezvous with Halley, we haven't had the support needed to make this a reality.

This same problem has been discussed recently in other contexts by Steven Weinberg who presented similar examples in theoretical physics and in astrophysics. One of these was the 3 K cosmological black body radiation and the question of why the history of its discovery was not similar to that of the neutrino. After all, it was predicted by theories of the origin of the universe. Nevertheless, it was discovered essentially independently of this prediction. Unlike the neutrino, it wasn't a major goal of observational astrophysicists to verify this prediction.

A similar situation occurred, as Weinberg also discussed, in the case of quantum electrodynamics. Discovery of the Lamb-Rutherford shift, predictable from quantum electrodynamics, came about independently of the theory. The fundamental reason for this situation, as identified by Weinberg, probably applies to our field as well. Deep-down, people didn't really believe that there was much connection between what the mathematicians, theorists, and speculators did while sitting at their desks playing their happy game and the real universe as observed through telescopes. Somehow there were two different worlds that didn't have much to do with one another.

This is an indication of a rather unhealthy state of affairs in a field of

science, and it is something that all of us must do something about. The developments that made the details of the "big-bang" theory of the origin of the universe respectable, and which made quantum electrodynamics respectable in spite of its infinities, and which brought us to the point where it was understood that there was some relationship between what people thought and what people saw, were new experimental observations. In the one case these were the actual measurements of the 3 K black body radiation and in the other case the Lamb-Rutherford shift in the spectrum of the hydrogen atom. It is likely that analogous observations will be required before scientific people take theories of the origin of the solar system seriously.

For example, imagine that a sample of Comet Encke was returned and the xenon extracted from this sample was analyzed. If this showed the mass fractionation which characterizes terrestrial xenon, there would be implanted deep in our consciousness the idea that there was some real substance to the story that we have heard several times this afternoon about the Earth's atmosphere, and even the precursors of terrestrial life, coming from comets. Observations of this sort would be the kind of thing which would really force our attention toward the reality of such speculations. I don't know where these observations are going to come from. Some of them have probably come already from measurements on meteorites. Others may be coming from astrophysical studies of interstellar clouds and star formation. I think the case has been made quite well today that perhaps the best opportunity for the type of revolutionary discoveries which will really bridge the gap between theory and experiment in this field will come from the detailed studies of comets through comet rendezvous and sample return missions.

(2) On Disequilibrium and Heterogeneity.

Another point that went through much of the discussion was the question

of equilibrium versus disequilibrium in the solar system. To a large extent,
our attempts to understand the solar system have proceeded from assumptions
of chemical equilibrium, partly because that is about the only thing one can
calculate, and the equilibrium condensation theories of Lewis and others have
had some measure of success.

However, it appears to me, as also pointed out by Bert Donn and others
in today's discussion, that perhaps the central message that we have learned
from the study of primitive material, such as the Allende meteorite, is the
prevalence of disequilibrium. In this meteorite, which is the sort of body
that one commonly associates with a low-temperature origin, are found the
highest temperature minerals of the condensation sequences. On a more detailed
scale, Robert Clayton reported oxygen isotopic disequilibria in this meteorite;
this was followed by discovery at Caltech and A.N.U. of anomalies in the magnesium
isotopes. These results were anticipated in earlier studies by Black of neon
anomalies in other meteorites. So the real characteristic of primitive material
as seen in the meteorites is disequilibrium, probably preserving pre-solar infor-
mation, rather than equilibrium. Furthermore this disequilibrium is accompanied
by heterogeneity. It is always simpler, and seems to some to be more honest
and less speculative and more in agreement with Occams Razor and similar principles
of that kind, to assume that things are homogeneous. However it almost always
seems that when you look at things carefully, they are not at all homogeneous,
but are highly heterogeneous. This is true of primitive objects such as the
carbonaceous meteorites and, for that matter, many of the ordinary chondrites
as well.

I think it will most likely turn out that when we go to the comets and
bring pieces of comets to our laboratories, we will find that they really
are heterogeneous disequilibrium assemblages. As Fred Whipple pointed out, his

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dirty snowball model has achieved considerable success, including some of the recent evidence which he showed us today of the splitting of comet West. Nevertheless, I don't think the snowball will turn out to be homogeneous. In our discussions over the last year in the Comet Halley Working Group, we spent much time talking about the proper minimum scale for imaging the comet nucleus—whether it was 1 cm or 1 meter or 100 meters. The problem was that we could not escape the belief that if we looked closer and closer, we would see more and more. The reason we stopped at one meter was because it seemed greedy to ask for more, not because we had any deeply held understanding as to where the information stopped. Just as in the case of the Allende meteorite, we probably will never predict all the wonderful things that will be found in cometary matter on the finest scale. It would be safe to say that anything we anticipate today, and that we have heard about today, will be an understatement of what we will learn when we are able to make sufficiently advanced and sophisticated measurements on this material.

(3) On Scientific Revolutions.

Brian Marsden said that what we really need at this time is a revolution comparable to those which Kepler and others achieved. I haven't experienced very many scientific revolutions. However, I was fortunate enough to have lived through one with which I was in some contact. This was the revolution in the earth sciences during the 1960's known as the plate tectonic revolution. Over a period of just a few years almost everyone's ideas regarding the primary forces which shape the surface features of the Earth were completely overturned. Perhaps one lesson about such revolutions which can be learned from this is that perhaps one should not be too self-conscious about it nor too much impressed by proposed "crucial experiments." Non-problem-oriented data gathered in the right places may do the job. In the early 1960's, the NSF had an Earth-Science Review

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Panel, just as they do today. The story is told that this panel spent the day reviewing various proposals and at the end of the day they met for cocktails and discussed the state of their field of science. It was agreed that on the whole the proposals reviewed were meritorious. There were many good things in them, but it didn't seem there was anything proposed that was really going to bring about a fundamental change in Earth science. This panel felt it their responsibility to do something about this and to think up a proposal which would really make a difference. This led to a champagne breakfast at La Jolla, and to the Mohole project, which might indeed have been a great thing if it had not fallen by the wayside.

However, at the same time that these leaders were planning the future of Earth science, there were people, often supported by Navy contracts, doing things like measuring magnetic fields at sea in a relatively unself-conscious way, and these turned out to be the measurements which led to the plate tectonic revolution. As I mentioned earlier, although it is very important that we get to the stage at which theoretical predictions should be taken seriously, one should also remember that the most important thing that brought about the plate tectonic revolution was simply that people were out there making good measurements in relevant places. In the case of the origin of the solar system, all kinds of primitive material are relevant, and the case for comet nuclei being a prime source of primitive material has been made very clearly by our various speakers. The primary task is to observe and analyze these nuclei in the most comple'? way possible.

(4) On Human History.

Although it was not discussed very much from the platform, we have heard some rather eloquent statements from the floor regarding the human adventure and the human history which is associated with Comet Halley. I think it would

be a mistake in our emphasis on the scientific value of these missions to
forget this.

I think that part of the mystique of Comet Halley is associated with the
fact that its period of 76 years is very nearly the length of a human lifetime.
As a consequence of this, our mothers can tell us that they saw Comet Halley in
1910, and we can tell our children that we saw it, and everyone can have the
opportunity to at least look forward to seeing it themselves. It is more than
a cliche to say "once in a lifetime." It doesn't take too many lifetimes to
take us back to Harold of Hastings and Atilla the Hun. So, quite apart from
speculations concerning whether or not our molecules descended from comets like
Halley 4.6 billion years ago, on the time scale of human history it is a faithful
marker. I don't think this has much to do with how bright Halley is, nor how
much of a spectacle it may be. It wasn't much of a spectacle in 1910. The
mystique of Halley is more related to its reliability, its predictability and
the regularity with which it has come back over and over again, through all of
human history. I think it is very important for scientists, including NASA
officials, to remember this, and to realize that between 1986 and the years 2062,
2138, and 2214, people all over the world will again be waiting and anticipating
Comet Halley's return. If we accomplish the rendezvous discussed today, this
achievement might then seem to mark a historically memorable start which led to
further glorious accomplishments. On the other hand it might appear as a beacon
from a more golden era, shining across the chasm of darker ages, a reminder of
the best that men can do. Either way, it will never be forgotten that we were
there.

END

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